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SPECIAL ASPECTS OF THE HYDRAULIC JUMP ON A SLOPING FLOOR

A DISSERTATION

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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ABSTRACT

The present status of the hydraulic jump theory on a horizontal floor and a sloped floor are discussed. The practical importance of the jump is mentioned and the differences between theory and research are emphasized. The results of a three-dimensional spillway model are treated from the viewpoint of the fundamental and practical observations usually omitted from conventional research. Ways to reduce uplift pressure by means of suction holes in chute blocks and the effect of chute blocks on the pressure distribution are discussed. The stresses in the water flowing on a slope are analyzed theoretically allowing for shear stresses.

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1. INTRODUCTION.

Although the hydraulic jump is the only effective means of dissipating energy within the confines of a spillway, the theory relating to the hydraulic jump is still very elementary and is only applicable to specially simple cases, such as the hydraulic jump on a horizontal floor without consideration of friction and velocity distribution. Experiments on the hydraulic jump have been restricted mainly to two-dimensional cases, simple boundary conditions and flow free from air entrainment. The average form of the hydraulic jump has been studied without consideration of the pressure caused by it. As a result of this, for a practical design, models are still needed, although the designer knows some of the results to be expected from the literature of basic jump studies. To remedy this situation the University of Alberta hopes to carry out basic model testing on a continuing programme to try to throw some light on the deficiences.

The author has taken advantage of a recent commercial model of a large spillway to concentrate attention on the fundamental and practical points that may merit later systematic investigation because they do not appear to have received the attention they deserve in the technical literature. Accordingly the status of theory and experiment are discussed at some length and then the experimental results are presented mainly to illustrate the points at issue. No attempt is made to give a full formal report of model testing such as can be obtained in general literature.

2. THEORETICAL BACKGROUND.

a. Jump on horizontal floor.

For many decades the hydraulic jump has been used as an energy dissipator for channel drops, but the only theoretically acceptable formula for it still remains that for:

1. A frictionless horizontal floor.
2. A fluid with a uniform velocity distribution before and after the jump.

The latter condition assumes the fluid to be frictionless internally. Although energy dissipation and thus the hydraulic jump could not occur under such circumstances, this absurdity does not have a serious practical effect. The formula for the conditions as mentioned above can be found in all elementary text-books that deal with open channel flow. This formula is now used with fair accuracy for a variety of practical problems. The correct mathematical theory of the hydraulic jump was apparently first worked out by the Frenchman Belanger in 1838. It was copied in Bresse's "Cours de Mecanique Appliquee", published in Paris in 1860. It was also copied in the article by Prof. W.C. Unwin in the ninth edition of the Encyclopedia Britannica about 1880. Before the formula was accepted and verified by experiments others tried to derive relationships between the depths up- and downstream of the jump, sometimes by neglecting the loss of energy in the jump.

The basic formula for the hydraulic jump on a horizontal frictionless floor, often called the jump equation, is stated for ready reference in the common text-book form as:

$$d_1 d_2 (d_1 + d_2) = 2 \frac{q^2}{g} \tag{1}$$

where d_1 = upstream depth

d_2 = downstream depth

q = discharge intensity

g = gravitational acceleration

It may also be written non-dimensionally as:

$$F_2 = 8F_1/(\sqrt{1 + 8F_1} - 1)^3 \tag{2}$$

where $F_1 = \frac{V_1^2}{gd_1}$ = Froude number before jump

$F_2 = \frac{V_2^2}{gd_2}$ = Froude number after jump

V_1 = velocity before jump

V_2 = velocity after jump

Finally a convenient and neat non-dimensional form for plotting is:

$$xy(x + y) = 2 \tag{3}$$

where $x = d_1/d_c$

$y = d_2/d_c$

d_c = critical depth = $\sqrt[3]{\frac{q^2}{g}}$

To practising engineers the loss of head over the jump is important since the hydraulic jump is used to dissipate head, so a formula showing the loss of head will be found in many practical references. From the fundamental equations it follows directly that the head loss (H_L) is given by:

$$H_L = (d_2 - d_1)^3/4d_1d_2 \qquad (4)$$

Writing this non-dimensionally in terms of d_c this becomes:

$$h_L = (y - x)^3/4xy \qquad (5)$$

where $h_L = H_L/d_c$

Use of equations (1) and (4) involves the solution of cubic equations. Although most text-books have neglected useable graphical presentations, specialist engineers have used them for several decades (Bibs. 12, 13, 14, 15). The author collaborated with Prof. T. Blench in the production of Plate 1, which is now in use at the University of Alberta and is intended to cover all possible design uses of the equations (3) and (5). This has not yet been published and its substance is the same as in the dimensional presentations of Bibs. 12, 13 and 14.

b. Jump on sloping floor.

As equation (1) shows, the hydraulic jump on a horizontal floor will form only at one d_2 for one d_1. Obviously it is impracticable to use such a jump for a spillway or a gate since

suitable conditions would occur only at one discharge. Friction would help the formation of the jump on a horizontal floor somewhat. Since the upstream watersurface profile is a class H_3 type of profile, if Streeter's notation is used (Bib. 1), as the supercritical jet runs along the floor the upstream depth d_1 is altered until equation (1) is satisfied. Since changes in depth of water with distance along the floor are very small, normally the jump could form too far from its desired position, which necessitates a long and costly stilling basin. Therefore the designer is compelled to provide a sloping floor so that an upstream and downstream depth combination can be found within the confines of the structure for every expected discharge. For a slope greater than 1:1 a submerged horizontal jump will form at the base of the steep slope so that there is a circulating roller on the top of the supercritical flow before the jump. If ordinary jump theory is applied to this, the jump appears impossible. An explanation for this is given by Blench in several publications (Bibs. 5, 16). For slopes less than 1:1, equation (1) does not apply either and the possibilities of uplift from the drainage bed under the floor could cause the spillway floor to fail (See Section 6). Therefore the designer wishes to know the form of the jump and the pressure distribution under it. Accordingly, a theoretical solution of the hydraulic jump on a slope would be most valuable to engineering practice. Unfortunately no theoretically acceptable formula has been derived, although several attempts have been made.

In 1917 the formation of a hydraulic jump on a sloped floor was first studied by Beebe and Riegel, who used a stepped apron instead of a sloped one. In 1928 Ellms presented a paper at a meeting of the American Society of Mechanical Engineers (Bib. 2). He discussed the methods of computing the tailwater depth when the jump occurs in a sloping flume. For this purpose he derived two experimental formulas. Ellms showed that the value for the downstream depth computed from the formula for a jump on a horizontal floor is much too great, when the jump is made to take place in a sloping flume. The flume used by Ellms diverged from 0.25 ft. to 0.67 ft. In his formula this divergence is not included and therefore it is not likely that his formulas can be used generally. Moreover the length of horizontal flume used in his experiments is too short to be able to measure the tailwater depth. The slopes tested were 0.3 and 0.22.

In a second paper presented by Ellms at a meeting of the American Society of Mechanical Engineers in 1932, a mathematical treatment is given for the jump on a sloping floor (Bib. 3). It should be noted that Ellms computed the tailwater depth wrongly. His equation was derived by using the momentum equation in the horizontal direction. However Ellms failed to recognize that the horizontal component of the hydrostatic pressure force exerted at the upstream end on the fluid mass considered is equal to:

$$\frac{1}{2}\gamma d_1^{\,2}\cos 2\alpha \text{ and not } \frac{1}{2}\gamma\frac{d_1^{\,2}}{\cos^2\alpha}$$

if d_1 is the depth of water measured perpendicular to the sloped chute, γ is the specific weight and α the angle between the floor and the horizontal (See Section 4). In his paper Ellms remarked that the observed readings in experiments conducted by him were all lower than the values computed from his formula.

Bakhmeteff and Matzke (Bib. 4) analyzed the jump on a sloping floor mathematically. They included the weight of the water between the two sections considered so as to include the pressure components in the horizontal direction. To include this factor in their formulas they used a profilo meter to establish the shape of the jump and they measured the pressures exerted by the water on the floor by means of manometers. They neglected the effect of the shear stresses and the extra pressure induced by the curvature of flow. Unfortunately the maximum slope tested was 7% for most of their experiments and not in the range in which most engineering structures are built.

3. EXPERIMENTAL INVESTIGATIONS.

Bakhmeteff and Matzke (Bib. 4) observed in their experiments that the supercritical jet plunges into the tailwater and follows the steeper portion of the floor with very little vertical expansion and small energy losses. The rapid expansion occurs

mainly in the reach of the mild slope or the horizontal floor. This was also found by Blench (Bib. 5) who showed the submerged jet with the fluid polariscope. It is interesting to note that Bakhmeteff and Matzke found that no appreciable difference could be observed between the depths and the local bottom pressures in feet of water.

Wigham (Bib. 6) conducted experiments with slopes of 1.0, 0.5 and 0.33 and measured the pressures exerted by the water on the steep and horizontal portions of the floor. The high pressures measured near the change in slope indicated that the supercritical jet continues as a submerged jet. The curvature of flow will increase the pressures above hydrostatic. It seemed however that for a greater downstream depth this phenomenon vanished and apparently there is a limiting value for the downstream depth. If the downstream depth is greater than this limiting value the supercritical jet will expand over the steep portion of the floor.

Woodward and Posey (Bib. 7) indicated that because of the unknown effect of viscosity, surface tension etc. experimental studies should be made on nearly full size models.

Kindsvater (Bib. 8) noted that for very steep slopes on large structures the problem is complicated by air entrainment and by the occurence of shock waves on the surface of the stream. This makes it virtually impossible to compute the momentum and the hydrostatic pressure near the toe of the hydraulic jump. It was verified by Kindsvater that the bottom pressures measured by piezometers checked very closely to the depths observed under the

hydraulic jump. It was observed in the tests described by Kindsvater that for an increased slope, an increasing length of vertical expansion is required for the supercritical jet and that the jump has a flatter appearance for increasing slopes. His experiments showed once more that the computed values, using the formulas in his paper, for the downstream depths, on the average lie above the observed downstream depths and that considerable scatter is present.

Bradley and Peterka (Bib. 10) analyzed the hydraulic jump on a sloped floor without trying to establish theoretical formulas. Because of the importance of their work and the close relation to the work carried out by the author, their results are discussed separately in sections 11-14.

4. THEORY OF NORMAL AND SHEAR STRESSES IN JETS.

In order to use Newton's second law of motion on a fluid mass in a supercritical jet on a sloped floor if terminal velocities are reached, it is necessary to know the magnitude and direction of the pressures exerted on that fluid mass. If friction is included the stress condition can be analyzed using Mohr's circle (Plate 2).

For the fluid element ABCD, the normal stress and the shear stress on face BC can be computed using conditions of equilibrium for the fluid column BCEF. If compressive stresses are taken as negative, and shear stresses positive if they produce clockwise

rotation of the element on which they act, we can write:

$$\sigma_{BC} = -\gamma d\cos^2\alpha$$

$$\tau_{BC} = +\gamma \frac{d}{2}\sin 2\alpha$$

Assuming that the shearing stresses will be maximum on the planes BC and AD parallel to the direction of flow, these conditions enable one to draw Mohr's circle for the case of the fluid element on the sloped floor. Point P on Mohr's circle (Plate 2) now represents the stress on a vertical plane. The magnitude of the normal stress (σ_v) can be found easily from Mohr's circle and is:

$$\sigma_v = -\sigma_{BC} + \tau_{BC}\sin 2\alpha$$

or $$\sigma_v = -\gamma d\cos^2\alpha + \gamma \frac{d}{2}\sin^2 2\alpha$$

which reduces to $$\sigma_v = -\gamma d\cos^2\alpha\cos 2\alpha$$

and thus makes the total compressive force per unit of width of spillway exerted on the fluid mass by the upstream water:

$$\text{force} = \tfrac{1}{2}\gamma d^2\cos^2\alpha\cos 2\alpha$$

The above shows that the total stress on a plane parallel to the sloped floor, when the velocity is terminal, is always in the vertical direction so that the weight of the fluid mass does not have to be considered to find the horizontal components of pressure if Newton's second law is applied in the horizontal direction to a hydraulic jump on a sloped floor.

5. MODEL STUDIES AT UNIVERSITY OF ALBERTA.

Because of the preceding considerations the author took advantage of a commercial model study with which he was associated at the University of Alberta. Points that seem to have escaped attention in the numerous, but restricted, experiments of the past decades were observed. The objects of this study were partly to ensure proper practical deductions from the model, partly to decide the best design for a later model to test the final design based on the first one and partly to obtain an insight into the basic problems that should be studied systematically in future years because of their fundamental and practical importance. Accordingly the remainder of this thesis deals only with the outstanding results of the model from these points of view and does not repeat information that can be obtained elsewhere. The model in question was for the "Squaw Rapids Development", located in Northern Saskatchewan on the Saskatchewan River near Tobin Rapids. The spillway was originally designed for a discharge of 240,000 c.f.s. with 6 bays of 40 feet width. The spillway diverged from 300 ft. at the crest to a 350 ft. wide stilling basin (See Plates 3 and 4). To study the general behaviour of the spillway a pilot model was built to a scale of 1:150 and the following points were studied among others on this model:

a. Behaviour of hydraulic jump.
b. Scour to bed and sides of the river downstream.
c. Spreading of supercritical jet.
d. Shock wave pattern.
e. Upstream wingwalls design.
f. Scour near upstream end of spillway.
g. Height of stilling basin walls.
h. Different type of sills.
i. Pressures exerted by the water over the spillway on the spillway floor.

To obtain some insight into the magnitude of the pressures exerted on the floor a section of the spillway was modeled to a scale of 1:60 in a glass walled flume and pressure measuring points were installed in the floor (See Plate 5). At the same time the profile of the hydraulic jump could be observed, subject to the restrictions of section 10.

6. IMPORTANCE OF KNOWLEDGE OF PRESSURES EXERTED ON THE FLOOR.

Many spillways and chutes failed in the past and probably will fail in the future because the designer did not fully appreciate the importance of uplift. Normally one would expect the pressures under the floor to be equivalent to a column of water rising to the elevation of the downstream water surface because of seepage

from downstream to points under the floor. In the case of cut-off walls this uplift pressure may be reduced for a certain period, but if the tailwater level persists for a long period, the hydrostatic pressure under the floor will correspond to the tailwater elevation eventually and more rapidly if aquifers are present. If the water in the chute is at a lower elevation than the tailwater elevation there is an unbalance of vertical forces and the floor may fail. By increasing the thickness of the concrete floor, and thus by increasing the vertical downward force, equilibrium can be reached. This however is a very costly procedure since the concrete thickness required can be quite large. For example for the Squaw Rapids Spillway one condition of discharge and tailwater requires a thickness of 15' of concrete. It is clear that in an economic design one will try to solve this problem in a less costly way.

7. REDUCTION OF UPLIFT DANGER.

Several methods can be devised to reduce the pressures under the floor or to increase the pressures above the floor.

a. Steeper slope.

A steeper slope will cause the profile of the jump to be much flatter and more equal to the tailwater elevation. This was outlined in Bib. 8 and is illustrated by photographs in Bib. 5. However often it is not feasible to increase the slope because of

other requirements of soil mechanics or structures. Frequently the spillway forms part of an earth dam and the slope is determined by the maximum allowable slope of the dam as determined by a stability analysis.

b. Perforated floor.

A perforated floor will provide a connection between the water above the floor and the water below the floor, thus equalising the pressure and eliminating uplift. However a solution of this kind cannot be used very well if the foundation material under the dam is not rocky. In the case of sand or other granular materials the pulsations of the water above the floor will suck the material from under the floor and endanger the stability of the spillway. This method can be used succesfully if the water above the floor is only present for a short time.

This method is used in similar form in the Netherlands to reduce pressures behind concrete slabs used as protection on sea-dikes. Several high waves will temporarily increase the pressure behind the slab. When the wave height is reduced without pressure release pipes the pressure behind the slab does not reduce quite as fast. Small pieces of pipe installed through the concrete slab however will enable the excess water behind the slabs to run off immediately and the pressure is reduced, thus eliminating the danger of sliding of the slabs.

c. Chute blocks.

The results of the tests carried out by the author showed that the installation of chute blocks will change the pressure distribution over the floor of the spillway so as to counterbalance uplift for certain tailwater conditions. A description of the test results will be found in section 9.

d. Baffles.

In smaller chutes or spillways baffle piers are used occasionally as energy dissipators. The author did not carry out tests to investigate the effect of the baffle piers on the pressure distribution over the floor. Because of turbulence and curvature of flow the pressure head readings would not mean much. However a description is given of tests carried out by others involving baffle piers and the results of these tests have been analyzed by the author in section 14.

e. Suction holes in the chute blocks.

The results of the tests carried out by the author showed that the pressure head measured at the downstream face of the chute blocks is lower than the depth of water at the chute blocks for certain conditions. By connecting the drainage bed under the floor to holes in the face of the chute blocks the pressure under the floor can be reduced. For a detailed description see section 9.

8. TESTING PROCEDURE.

In order to find the effect of chute blocks and a dentated sill on the pressure distribution over a spillway a flume to a scale of 1:60 was built in which a sloping floor (4 vert. to 10 hor.) was installed. The width of the flume was taken as 12 inches. Plate 5 shows the major dimensions of the flume. The tailwater elevation was regulated by a weir at the downstream end. An undershot gate was used to pond up the water in the reservoir to the necessary elevation. At several points on the chute floor pressure measuring points were installed. In order to reduce the pressure fluctuations to a minimum little porous bronze plates were used. These plates had a dampening effect on the pressure fluctuations as did the inertia of the liquid in the plastic tubing and in the manometer bank; the menisci in the manometers actually remained almost perfectly at rest. However readings were not taken to a greater accuracy than one prototype foot, since inevitable scale distortions and the prototype conditions did not justify greater exactness. The bronze plates were set so that they did not protrude above the chute floor. After the model was not used for some time the action of the water on the plywood used in the construction of the model warped the plywood slightly and caused the floor to come up a bit and thus the readings for tests without chute blocks were effected. A correction was applied for this. The location of the pressure points is indicated on plate 5. Pressure points 5, 8, 11, 14 are located 3 inches from the centerline of

the flume. The discharge was measured by means of a rotameter bank containing a 2 inch, a 3 inch and a 4 inch rotameter. The discharges run were 0.892 c.f.s., 0.322 c.f.s., 0.655 c.f.s. and 1.258 c.f.s. These discharges correspond to prototype discharges of 50,000 c.f.s., 100,000 c.f.s., 141,500 c.f.s. and app. 200,000 c.f.s. The gate was raised to a level such that the water elevation in the reservoir stayed constant and at a level corresponding to the prototype conditions. After the flow reached a steady state the manometers were read for different tailwater elevations. Tests were run without chute blocks and a dentated sill and with chute blocks and a dentated sill in order to compare the results. The height of the chute blocks used in the model was 1.65 inches and the sill was 2.15 inches. These dimensions correspond to prototype dimensions of 8.25 feet and 10.75 feet respectively. In the case of the tests with the chute blocks in place a manometer was connected to the suction hole in the face of one of the chute blocks (See Plate 5). To facilitate the processing of the data the elevations of the pressure head were read to a scale of 1:60 so that they could be applied to the prototype without conversion.

9. TEST RESULTS.

The results of the tests are tabulated in the appendix and plotted on plates 6 to 17. The pressures and the distances are plotted non-dimensionally as was first done by Wigham (Bib. 6). This enables one to compare the test results for different

discharges. The graphs on plates 6 to 17 show that for a high tailwater elevation a class "D" or "C" type of jump is formed (Plate 18) and that the effect of the chute blocks and the sill on the pressure distribution is negligible. A lowering of the tailwater elevation will cause a jump of type "B" to form. The effect of the chute blocks on the pressure distribution now becomes noticeable. The chute blocks cause the jump to occur further up the slope and the pressure over the zone of subcritical flow is higher, thereby reducing the danger of uplift. It becomes apparent that the classic jump classification given in Plate 18 is not sufficient to describe whether chute blocks have an effect on the pressure distribution. Only if the supercritical jet continues along the sloped portion of the chute will the chute blocks have any effect. Therefore a classification of jump profiles in the case of chute blocks should be based upon the absence or presence of the supercritical jet at the bottom of the slope. From the tests conducted and for a slope of 0.4:1 this turning point seems to be at a downstream non-dimensional pressure head of 3. Since the pressure head measured is equal to the depth, a non-dimensional tailwater depth of 3 or less will be necessary to get any favourable effect from the chute blocks with respect to the pressure distribution for the slope of 0.4:1. If the non-dimensional tailwater depth is more than 3, it is quite useless to install friction blocks to improve the pressure distribution. For non-dimensional tailwater depths of 3 or less the pressure distribution at the bottom of the sloped portion of the floor is not hydrostatic. Because of curvature of flow the pressure is increased above hydrostatic, thereby indicating the presence of

a high speed jet at the bottom of the slope.

The above reasoning does not seem to hold for the test results plotted on plates 16 and 17. The graphs indicate that the jump occurs somewhat further up the slope for the case without chute blocks. However, photographs taken during these tests (Plates 24, 25, 26, 27) show that the chute blocks do cause the jump to occur further up the slope and therefore it must be assumed that either the manometer readings are not correct or the different appearance of the jump if no friction blocks are present may be responsible for a different pressure distribution. Future research may answer this problem.

The pressures measured in the suction hole in the face of one of the chute blocks, as shown on the graphs, indicate that for lower tailwater elevations the pressures measured are lower or the suction higher. Use of this suction can be made to decrease the danger of uplift. By connecting the drainage bed under the floor to the face of the chute blocks the water pressures under the floor will be reduced. The danger of using this system to decrease the pressures under the floor lies in the possibility of the drains clogging up, and thereby becoming less effective. If the dead weight of the concrete alone is not enough to counterbalance the uplift forces, failure of the spillway could result. It is doubtful how effective the suction holes in the chute blocks are if air is entrained, since the jet velocity is then reduced. Future investigations will have to give an answer to this problem.

10. COMPARISON BETWEEN 3-DIMENSIONAL AND 2-DIMENSIONAL MODEL.

Many designers do not quite realize the importance of a model study in three dimensions. The author will try to demonstrate in this section that the application of results found in a two-dimensional model cannot always be applied to the three-dimensional prototype. The author was fortunate to be able to compare a two-dimensional and a three-dimensional model of a spillway. To check the general design of the spillway a three-dimensional model was built to a scale of 1:150. To get more specific information about the pressures exerted on the spillway floor a two-dimensional model was built to a scale of 1:60. The major differences between a two-dimensional and a three-dimensional model are:

a. Influence of shock wave pattern.

b. Difference in friction at the sides.

The influence of the shock waves set up by the piers is emphasized if the spillway diverges. Due to the shock waves the discharge intensity and the depth of flow will vary over the width of the spillway. This will cause the hydraulic jump to form further down the slope at those sections of the spillway where the depth is greater and further up the slope where the depth is less. This will give the hydraulic jump a "ragged" look as is clearly demonstrated by the photograph on plate 19 where the region of high discharge intensity is in the center of the spillway. Ippen (Bib. 11) has analyzed the shock waves theoretically by assuming

them to be small hydraulic jumps. This way he could show that in the case of a diverging spillway the discharge intensity will be higher near the centerline of the spillway than near the sides. In the case of a two-dimensional model the discharge intensity is nearly uniform and the results obtained in the two-dimensional model can therefore only be applied to that section of the three-dimensional prototype where the discharge intensity and the depth are equal in model and prototype.

The influence of the friction is pronounced especially if the structure is not symmetrical as was the case for the model tested. Plate 3 shows a lay-out of the spillway. The greatest scour developed near point A. The asymmetrical location of the scour-hole can be explained if one realizes that the right riverbank tries to slow down the water because of friction. A backroller results and vertical vortices are induced that will augment the bed scour. This means that especially for scour studies a two-dimensional model is very unreliable since it cannot represent prototype conditions.

11. TESTS CONDUCTED BY BRADLEY AND PETERKA.

Bradley and Peterka published several papers (Bib. 10) in 1957 in which they discussed experiments carried out on the hydraulic jump on sloping floors with chute blocks, baffle piers and sills. All their tests were carried out in two-dimensional models. They produced curves for the computation of the hydraulic

jump on a sloping floor, but they failed to emphasize the fact that their results cannot be applied to the three-dimensional prototype without consideration of the points mentioned in section 10. The tests they carried out, however, are very useful and the author has used them to complete his own work. The types of stilling basins tested were classified as shown on plate 20.

12. BASIN I.

From the data published by Bradley and Peterka (Bib. 10) the author computed the non-dimensional energy loss and the non-dimensional tailwater depth at sweep-out. For the tailwater depth at sweep-out ($T_{s.o.}$), the downstream depth for the case of the toe of the jump occurring at the bottom of the steep slope was taken, since a further decrease in tailwater elevation would cause the jump to move off the structure (See Plate 20). The figures obtained from the results of Bradley and Peterka were plotted non-dimensionally together with the results obtained by Wigham (Bib. 6) on plate 21. It appears that the plotted points follow the theoretical curve h_L versus e_{f2} from plate 1 for the hydraulic jump on a horizontal floor very closely. This means that the minimum allowable tailwater depth for Basin I can be found by applying the formulas for the hydraulic jump on a horizontal floor.

13. BASIN II.

Treating Bradley and Peterka's results similarly, as described in section 12, it appears that the effect of the chute blocks and the dentated sill on the minimum allowable tailwater depth is very small as compared to the necessary depth for the jump on a horizontal floor, although it becomes more pronounced for lower tailwater depths (Plate 22). It is not quite clear from the obtained results what the influence of the slope is for lower non-dimensional tailwater depths, since the data did not cover this very important range. Future testing should be carried out to extend the data.

14. BASIN III.

In the case of chute blocks, baffle piers and a dentated sill it is apparent from plate 23 that the minimum allowable tailwater depth is reduced considerably as compared to the depth required on a horizontal floor. For this case future testing must be carried out to supplement the data. It should be noted that this type of stilling basin is only used for small structures.

15. CONCLUSIONS.

1. The suction at chute blocks can be used to reduce uplift from the drains under a chute.
2. The effectiveness of chute block suction at low discharges depends on the persistence of the jet beneath the roller and has not been studied adequately.
3. Persistence of jet beneath the roller appears sufficient to compel cognisance of shear stress in theoretical studies of jump on slopes. At present shear stress is ignored.
4. Supercritical chute divergence is of great potential economic value and has been ignored in most studies. But it produces non uniform discharge intensity distribution at the jump.
5. For simpler cases simple shock wave theory will predict divergence of flow. The less simple cases are practically important, probably theoretically tractable, and can certainly be analyzed by a model.
6. For extension of model work to prototype the effect of air entrainment on chute block suction and on jump pressure distribution are both of vital importance. Nothing effective can be predicted about them at present, but work on air entrainment on laboratory chutes suggests that answers could be obtained.
7. Even asymmetry of exit conditions from an otherwise symmetrical work can alter scour pattern radically. And the possibilities

of asymmetric spillways for special cases are considerable and seem susceptible to basic analysis.

8. A two-dimensional spillway model is usually insufficient for designing a three-dimensional diverging spillway prototype.
9. Prototype observations are necessary to supplement model predictions.
10. In practice lower discharges may be more dangerous under suitable downstream gauge-discharge relations, than higher ones and may subject the top of the chute rather then the bottom to unbalanced uplift.
11. The conditions for the jump on a slope sweeping off the horizontal floor are represented closely by the theoretical curves for the jump on a horizontal floor.

BIBLIOGRAPHY.

1. V.L. Streeter:
Fluid Mechanics (McGraw-Hill).

2. R.W. Ellms:
Computation of tailwater depth of the hydraulic jump in sloping flumes, paper Hyd. 50-5, Transactions, American Society of Mechanical Engineers, vol. 50, no. 36, pp. 1-6, September-December, 1928.

3. R.W. Ellms:
Hydraulic jump in sloping and horizontal flumes, paper Hyd. 54-6, Transactions, American Society of Mechanical Engineers, vol. 54, no. 22, pp. 113-119, November, 1932.

4. B.A. Bakhmeteff and A.E. Matzke:
The hydraulic jump in sloped channels, paper Hyd. 60-1, Transactions, American Society of Mechanical Engineers, vol. 60, no. 2, pp. 111-118, February, 1938.

5. T. Blench:
Scour in alluvium below falls, paper appendix 20, International Association for Hydraulic Structures Research, Report on the second meeting, Stockholm, 1948, pp. 341-350.

6. J.M. Wigham:
An experimental determination of the fluid pressures exerted on spillway floors, Dissertation for the degree of Master of Science, University of Alberta, September, 1958.

7. S.M. Woodward and C.J. Posey:
Hydraulics of steady flow in open channels (Wiley).

8. C.E. Kindsvater:
The hydraulic jump in sloping channels, Transactions, American Society of Civil Engineers, vol. 109, pp. 1107-1120, 1944.

9. V.T. Chow:
Open channel hydraulics (McGraw-Hill).

10. J.N. Bradley and A.J. Peterka:
Hydraulic design of stilling basins and bucket energy dissipators, Engineering monographs, no. 25, United States Department of the Interior, Bureau of Reclamation, 1958.
(See also: Journal of the Hydraulics Division of the American Society of Civil Engineers, October, 1957, no. 1401-1406.

BIBLIOGRAPHY (cont'd).

11. A.T. Ippen and D.R.F. Harkman:
Verification of theory for oblique standing waves, Transactions, American Society of Civil Engineers, vol. 121, pp. 678-694, 1956.

12. Central Board of Irrigation, Simla, India:
The standing wave or hydraulic jump, publication no. 7, 1934.

13. Central Board of Irrigation, Simla, India:
Energy of flow, pressure and momentum diagrams, publication no. 4, 1934.

14. Central Board of Irrigation, Simla, India:
Design of weirs on permeable foundations, publication no. 12, 1936.

15. H.A. Babcock:
Tabular solution of open channel flow equations, Proceedings, American Society of Civil Engineers, HY 3, paper no. 1961, March, 1959.

16. T. Blench:
Standing wave problems, The Engineer of Aug. 6, 1937, Aug. 13, 1937 and Aug. 20, 1937.

LOCATION AND ELEVATION OF PRESSURE POINTS IN PROTOTYPE DIMENSIONS.

Model scale: 1:60.

Pressure point No.	Prototype elevation in feet for tests with chute blocks.	Corrected prototype elevation in feet for tests without chute blocks.	Prototype distance in feet from hinge.	Remarks.
1	905	905	+ 172.50	on horizontal floor
2	905	905	+ 82.50	" " "
3	905	905	+ 37.50	" " "
4	905	905	+ 7.50	" " "
5	915.7	916.2	- 26.69	on sloped floor
6	915.7	916.2	- 26.69	" " "
7	921.3	921.8	- 40.60	" " "
8	926.8	927.3	- 54.55	" " "
9	926.8	927.3	- 54.55	" " "
10	932.4	932.9	- 68.47	" " "
11	937.3	937.8	- 82.40	" " "
12	937.3	937.8	- 82.40	" " "
13	941.2	941.7	- 96.33	" " "
14	944	944.5	- 110.26	" " "
15	944	944.5	- 110.26	" " "
16	945.7	946.2	- 124.19	" " "
17	946.7	947.2	- 152.04	" " "
18				suction in chute block face
19				tailwater

DATA SHEET FOR TEST NO. 60A1.

Model discharge:	0.322 c.f.s.
Prototype discharge:	50,000 c.f.s.
Critical depth model:	0.148 ft.
Critical depth prototype:	8.86 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	952.5	47.5	5.36	+ 19.48
2	952	47	5.30	+ 9.31
3	951.5	46.5	5.25	+ 4.23
4	951.5	46.5	5.25	+ 0.85
5	950	34.3	3.87	- 3.01
6	950	34.3	3.87	- 3.01
7	948.5	27.2	3.07	- 4.48
8	948.5	21.7	2.45	- 6.16
9	947.5	20.7	2.34	- 6.16
10	946.5	14.1	1.59	- 7.73
11	947	9.7	1.09	- 9.29
12	947.5	10.2	1.15	- 9.29
13	947	5.8	0.65	- 10.87
14	948	4.0	0.45	- 12.44
15	948.5	4.5	0.51	- 12.44
16	950.5	4.8	0.54	- 14.00
17	950.5	3.8	0.43	- 17.16
18	949.5	44.5	5.02	
19	952	47	5.30	

DATA SHEET FOR TEST NO. 60A2.

Model discharge:	0.322 c.f.s.
Prototype discharge:	50,000 c.f.s.
Critical depth model:	0.148 ft.
Critical depth prototype:	8.86 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	947	42	4.74	+ 19.48
2	946.5	41.5	4.69	+ 9.31
3	946	41	4.63	+ 4.23
4	945.5	40.5	4.57	+ 0.85
5	944	28.3	3.19	- 3.01
6	944	28.3	3.19	- 3.01
7	942.5	21.2	2.39	- 4.48
8	943	16.2	1.83	- 6.16
9	942	15.2	1.72	- 6.16
10	943	10.6	1.20	- 7.72
11	943.5	6.2	0.70	- 9.29
12	943.5	6.2	0.70	- 9.29
13	947	5.8	0.66	- 10.87
14	948.5	4.5	0.51	- 12.44
15	948.5	4.5	0.51	- 12.44
16	951	5.3	0.60	- 14.00
17	951	4.3	0.49	- 17.16
18	943	38	4.28	
19	946.5	41.5	4.69	

DATA SHEET FOR TEST NO. 60A3.

Model discharge:	0.322 c.f.s.
Prototype discharge:	50,000 c.f.s.
Critical depth model:	0.148 ft.
Critical depth prototype:	8.86 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	941.5	36.5	4.12	+ 19.48
2	940.5	35.5	4.01	+ 9.31
3	940	35	3.95	+ 4.23
4	939.5	34.5	3.90	+ 0.85
5	937.5	21.8	2.46	- 3.01
6	937	21.3	2.41	- 3.01
7	937	15.7	1.77	- 4.48
8	938.5	11.7	1.32	- 6.16
9	937	10.2	1.15	- 6.16
10	938.5	6.1	0.69	- 7.72
11	943	5.7	0.64	- 9.29
12	943.5	6.2	0.70	- 9.29
13	947	5.8	0.66	- 10.87
14	948.5	4.5	0.51	- 12.44
15	947.5	3.5	0.39	- 12.44
16	951	5.3	0.60	- 14.00
17	951	4.3	0.49	- 17.16
18	934	29	3.17	
19	941	36	4.06	

DATA SHEET FOR TEST NO. 60AN1.

Model discharge:	0.322 c.f.s.
Prototype discharge:	50,000 c.f.s.
Critical depth model:	0.148 ft.
Critical depth prototype:	8.86 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	951	46	5.19	+ 19.48
2	952	47	5.31	+ 9.31
3	951.5	46.5	5.26	+ 4.23
4	952	47	5.31	+ 0.85
5	950	33.8	3.82	- 3.01
6	out			- 3.01
7	948	26.2	2.96	- 4.48
8	948	20.7	2.34	- 6.16
9	948.5	21.2	2.39	- 6.16
10	947.5	14.6	1.65	- 7.72
11	947	9.2	1.04	- 9.29
12	947.5	9.7	1.09	- 9.29
13	949	7.3	0.82	- 10.87
14	950	5.5	0.62	- 12.44
15	948	3.5	0.39	- 12.44
16	952	5.8	0.66	- 14.00
17	954	6.8	0.77	- 17.16
18				
19	952	47	5.31	

DATA SHEET FOR TEST NO. 60AN2.

Model discharge:	0.322 c.f.s.
Prototype discharge:	50,000 c.f.s.
Critical depth model:	0.148 ft.
Critical depth prototype:	8.86 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	947	42	4.74	+ 19.48
2	946	41	4.63	+ 9.31
3	945.5	40.5	4.57	+ 4.23
4	946	41	4.63	+ 0.85
5	943	26.8	3.03	- 3.01
6	out			- 3.01
7	942.5	20.7	2.34	- 4.48
8	944	16.7	1.89	- 6.16
9	944	16.7	1.89	- 6.16
10	943.5	10.6	1.20	- 7.73
11	944.5	6.7	0.76	- 9.29
12	945	7.2	0.81	- 9.29
13	949	7.3	0.82	- 10.87
14	950	5.5	0.62	- 12.44
15	948	3.5	0.39	- 12.44
16	952	5.8	0.66	- 14.00
17	954	6.8	0.77	- 17.16
18				
19	946.5	41.5	4.69	

DATA SHEET FOR TEST NO. 60AN3.

Model discharge:	0.322 c.f.s.
Prototype discharge:	50,000 c.f.s.
Critical depth model:	0.148 ft.
Critical depth prototype:	8.86 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	942	37	4.18	+ 19.48
2	941	36	4.06	+ 9.31
3	939.5	34.5	3.90	+ 4.23
4	939.5	34.5	3.90	+ 0.85
5	937	20.8	2.35	- 3.01
6	out			- 3.01
7	938	16.2	1.83	- 4.48
8.	940.5	13.2	1.49	- 6.16
9	939.5	12.2	1.38	- 6.16
10	940	7.1	0.80	- 7.73
11	944.5	6.7	0.76	- 9.29
12	945	7.2	0.81	- 9.29
13	949	7.3	0.82	- 10.87
14	950	5.5	0.62	- 12.44
15	948	3.5	0.39	- 12.44
16	952	5.8	0.66	- 14.00
17	954	6.8	0.77	- 17.16
18				
19	941.5	36.5	4.12	

DATA SHEET FOR TEST NO. 60E1.

Model discharge:	0.655 c.f.s.
Prototype discharge:	100,000 c.f.s.
Critical depth model:	0.237 ft.
Critical depth prototype:	14.21 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	946.5	41.5	2.92	+ 12.10
2	942.5	37.5	2.64	+ 5.80
3	940	35	2.46	+ 2.64
4	943.5	38.5	2.71	+ 0.53
5	942	26.3	1.85	- 1.88
6	939.5	23.8	1.67	- 1.88
7	937.5	16.2	1.04	- 2.85
8	938	11.2	0.79	- 3.84
9	936	9.2	0.65	- 3.84
10	940	7.6	0.53	- 4.81
11	944	6.7	0.47	- 5.79
12	944.5	7.2	0.51	- 5.79
13	948.5	7.3	0.51	- 6.77
14	949.5	5.5	0.39	- 7.75
15	948.5	4.5	0.32	- 7.75
16	952	6.3	0.44	- 8.72
17	953	6.3	0.44	- 10.69
18	927.5	22.5	1.58	
19	946	41	2.87	

DATA SHEET FOR TEST NO. 60E2.

Model discharge:	0.655 c.f.s.
Prototype discharge:	100,000 c.f.s.
Critical depth model:	0.237 ft.
Critical depth prototype:	14.21 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	951.5	46.5	3.27	+ 12.10
2	948.5	43.5	3.06	+ 5.80
3	946.5	41.5	2.92	+ 2.64
4	949	44	3.09	+ 0.53
5	946.5	30.8	2.17	- 1.88
6	944	28.3	1.99	- 1.88
7	943.5	22.2	1.56	- 2.85
8	944	17.2	1.21	- 3.84
9	942.5	15.7	1.10	- 3.84
10	942	9.6	0.66	- 4.81
11	943.5	6.2	0.44	- 5.79
12	944.5	7.2	0.51	- 5.79
13	948.5	7.3	0.51	- 6.77
14	949	5	0.35	- 7.75
15	949	5	0.35	- 7.75
16	952	6.3	0.44	- 8.72
17	953	6.3	0.44	- 10.69
18	937	32	2.25	
19	951	46	3.23	

DATA SHEET FOR TEST NO. 60E3.

Model discharge:	0.655 c.f.s.
Prototype discharge:	100,000 c.f.s.
Critical depth model:	0.237 ft.
Critical depth prototype:	14.21 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	956.5	51.5	3.62	+ 12.10
2	954.5	49.5	3.48	+ 5.80
3	952.5	47.5	3.34	+ 2.64
4	955	50	3.51	+ 0.53
5	952	36.3	2.55	- 1.88
6	950	34.3	2.41	- 1.88
7	949	27.7	1.95	- 2.85
8	949	22.2	1.56	- 3.84
9	948	21.2	1.49	- 3.84
10	948	15.6	1.10	- 4.81
11	946	8.7	0.61	- 5.79
12	947	9.7	0.68	- 5.79
13	948.5	7.3	0.51	- 6.77
14	949	5	0.35	- 7.75
15	948	4	0.28	- 7.75
16	952.5	6.8	0.48	- 8.72
17	953	6.3	0.44	- 10.69
18	946	41	2.88	
19	956.5	51.5	3.62	

DATA SHEET FOR TEST NO. 60EN1.

Model discharge:	0.655 c.f.s.
Prototype discharge:	100,000 c.f.s.
Critical depth model:	0.237 ft.
Critical depth prototype:	14.21 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	946	41	2.88	+ 12.10
2	941	36	2.53	+ 5.80
3	937	32	2.25	+ 2.64
4	942	37	2.60	+ 0.53
5	937	20.8	1.46	- 1.88
6	out			- 1.88
7	937	15.2	1.07	- 2.85
8	939.5	12.2	0.86	- 3.84
9	939	11.7	0.82	- 3.84
10	942	9.1	0.64	- 4.81
11	944.5	6.7	0.47	- 5.79
12	945	7.2	0.51	- 5.79
13	950	8.3	0.58	- 6.77
14	951	6.5	0.46	- 7.75
15	949.5	5	0.35	- 7.75
16	953	6.8	0.48	- 8.72
17	956	8.8	0.62	- 10.69
18				
19	946	41	2.88	

DATA SHEET FOR TEST NO. 60EN2.

Model discharge:	0.655 c.f.s.
Prototype discharge:	100,000 c.f.s.
Critical depth model:	0.237 ft.
Critical depth prototype:	14.21 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	950	45	3.16	+ 12.10
2	947.5	42.5	2.99	+ 5.80
3	945	40	2.81	+ 2.64
4	943.5	38.5	2.71	+ 0.53
5	943	26.8	1.88	- 1.88
6	out			- 1.88
7	944	22.2	1.56	- 2.85
8	944.5	17.2	1.21	- 3.84
9	944	16.7	1.17	- 3.84
10	942.5	9.6	0.68	- 4.81
11	944.5	6.7	0.47	- 5.79
12	945	7.2	0.51	- 5.79
13	950	8.3	0.58	- 6.77
14	951	6.5	0.46	- 7.75
15	950	5.5	0.39	- 7.75
16	953	6.8	0.48	- 8.72
17	956	8.8	0.62	- 10.69
18				
19	951.5	46.5	3.27	

DATA SHEET FOR TEST NO. 60EN3.

Model discharge:	0.655 c.f.s.
Prototype discharge:	100,000 c.f.s.
Critical depth model:	0.237 ft.
Critical depth prototype:	14.21 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	956	51	3.59	+ 12.10
2	954	49	3.45	+ 5.80
3	951.5	46.5	3.27	+ 2.64
4	954.5	49.5	3.48	+ 0.53
5	949	32.8	2.31	- 1.88
6	out			- 1.88
7	949	27.2	1.91	- 2.85
8	950	22.7	1.59	- 3.84
9	949	21.7	1.52	- 3.84
10	949	16.1	1.13	- 4.81
11	945.5	7.7	0.54	- 5.79
12	946.5	8.7	0.61	- 5.79
13	950.5	8.8	0.62	- 6.77
14	951	6.5	0.46	- 7.75
15	949.5	5	0.35	- 7.75
16	953	6.8	0.48	- 8.72
17	956	8.8	0.62	- 10.69
18				
19	956.5	51.5	3.62	

DATA SHEET FOR TEST NO. 6001.

Model discharge:	0.892 c.f.s.
Prototype discharge:	141,500 c.f.s.
Critical depth model:	0.292 ft.
Critical depth prototype:	17.5 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	948	43	2.46	+ 9.86
2	940	35	2.00	+ 4.72
3	937	32	1.83	+ 2.15
4	947	42	2.40	+ 0.43
5	942	26.3	1.51	- 1.53
6	939	23.3	1.33	- 1.53
7	935	13.7	0.78	- 2.32
8	939.5	12.7	0.73	- 3.12
9	939.5	12.7	0.73	- 3.12
10	941	8.6	0.49	- 3.92
11	944	6.7	0.38	- 4.72
12	944.5	7.2	0.41	- 4.72
13	949	7.8	0.45	- 5.51
14	950	6	0.34	- 6.32
15	948	4	0.23	- 6.32
16	952.5	6.8	0.39	- 7.11
17	954.5	7.8	0.45	- 8.90
18	916.5	11.5	0.66	
19	946.5	41.5	2.37	

DATA SHEET FOR TEST NO. 6002.

Model discharge:	0.892 c.f.s.
Prototype discharge:	141,500 c.f.s.
Critical depth model:	0.292 ft.
Critical depth prototype:	17.5 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	953	48	2.75	+ 9.86
2	946.5	41.5	2.37	+ 4.72
3	944	39	2.23	+ 2.15
4	951.5	46.5	2.66	+ 0.43
5	948	32.3	1.84	- 1.53
6	944.5	28.8	1.65	- 1.53
7	942	20.7	1.19	- 2.32
8	941.5	14.7	0.84	- 3.12
9	938.5	11.7	0.67	- 3.12
10	941.5	9.1	0.52	- 3.92
11	944	6.7	0.38	- 4.72
12	945	7.7	0.44	- 4.72
13	949	7.8	0.45	- 5.51
14	950	6	0.34	- 6.32
15	948.5	4.5	0.26	- 6.32
16	952.5	6.8	0.39	- 7.11
17	955	8.3	0.47	- 8.90
18	929	24	1.37	
19	952	47	2.69	

DATA SHEET FOR TEST NO. 6003.

Model discharge:	0.892 c.f.s.
Prototype discharge:	141,500 c.f.s.
Critical depth model:	0.292 ft.
Critical depth prototype:	17.5 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	958	53	3.03	+ 9.86
2	953	48	2.75	+ 4.72
3	951	46	2.63	+ 2.15
4	956.5	51.5	2.95	+ 0.43
5	952.5	36.8	2.11	- 1.53
6	950	34.3	1.96	- 1.53
7	948	26.7	1.53	- 2.32
8	948	21.2	1.21	- 3.12
9	947	20.2	1.16	- 3.12
10	945	12.6	0.72	- 3.92
11	944.5	7.2	0.42	- 4.72
12	945.5	8.2	0.47	- 4.72
13	949	7.8	0.45	- 5.51
14	950	6	0.34	- 6.32
15	948.5	4.5	0.26	- 6.32
16	952.5	6.8	0.39	- 7.11
17	955	8.3	0.47	- 8.90
18	940	35	2.00	
19	958	53	3.03	

DATA SHEET FOR TEST NO. 600N1.

Model discharge:	0.892 c.f.s.
Prototype discharge:	141,500 c.f.s.
Critical depth model:	0.292 ft.
Critical depth prototype:	17.5 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	944	39	2.23	+ 9.86
2	932.5	27.5	1.57	+ 4.72
3	929	24	1.37	+ 2.15
4	940.5	35	2.00	+ 0.43
5	931.5	15.3	0.88	- 1.53
6	out			- 1.53
7	936.5	14.7	0.84	- 2.32
8	941.5	14.2	0.81	- 3.12
9	941	13.7	0.78	- 3.12
10	943	10.1	0.58	- 3.92
11	945	7.2	0.41	- 4.72
12	946	8.2	0.47	- 4.72
13	951	9.3	0.53	- 5.51
14	951.5	7	0.40	- 6.32
15	948.5	4	0.23	- 6.32
16	953.5	7.3	0.42	- 7.11
17	957.5	10.3	0.59	- 8.90
18				
19	947	42	2.40	

DATA SHEET FOR TEST NO. 600N2.

Model discharge:	0.892 c.f.s.
Prototype discharge:	141,500 c.f.s.
Critical depth model:	0.292 ft.
Critical depth prototype:	17.5 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	950.5	45.5	2.60	+ 9.86
2	944	39	2.23	+ 4.72
3	941	36	2.06	+ 2.15
4	949	44	2.52	+ 0.43
5	939.5	23.3	1.35	- 1.53
6	out			- 1.53
7	939.5	17.7	1.01	- 2.32
8	941.5	14.2	0.81	- 3.12
9	941.5	14.2	0.81	- 3.12
10	943	10.1	0.58	- 3.92
11	945	7.2	0.41	- 4.72
12	946	8.2	0.47	- 4.72
13	951	9.3	0.53	- 5.51
14	952	7.5	0.43	- 6.32
15	948.5	4	0.23	- 6.32
16	953.5	7.3	0.42	- 7.11
17	957.5	10.3	0.59	- 8.90
18				
19	952.5	47.5	2.72	

DATA SHEET FOR TEST NO. 600N3.

Model discharge:	0.892 c.f.s.
Prototype discharge:	141,500 c.f.s.
Critical depth model:	0.292 ft.
Critical depth prototype:	17.5 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	956	51	2.92	+ 9.86
2	951.5	46.5	2.66	+ 4.72
3	949	44	2.58	+ 2.15
4	955	50	2.86	+ 0.43
5	947	30.8	1.76	- 1.53
6	out			- 1.53
7	947.5	25.7	1.47	- 2.32
8	947.5	20.2	1.16	- 3.12
9	947	19.7	1.13	- 3.12
10	944.5	11.6	0.66	- 3.92
11	945	7.2	0.41	- 4.72
12	946	8.2	0.47	- 4.72
13	951	9.3	0.53	- 5.51
14	952	7.5	0.43	- 6.32
15	949	4.5	0.26	- 6.32
16	953.5	7.3	0.42	- 7.11
17	957.5	10.3	0.59	- 8.90
18				
19	958	53	3.03	

DATA SHEET FOR TEST NO. 60X1.

Model discharge:	1.258 c.f.s.
Prototype discharge:	200,000 c.f.s.
Critical depth model:	0.367 ft.
Critical depth prototype:	22 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	955	50	2.27	+ 7.83
2	941	36	1.64	+ 3.75
3	938	33	1.50	+ 1.70
4	952.5	47.5	2.16	+ 0.34
5	944.5	28.8	1.31	- 1.21
6	941.5	25.8	1.17	- 1.21
7	937	15.7	0.71	- 1.84
8	940.5	13.7	0.62	- 2.48
9	938	11.2	0.51	- 2.48
10	941.5	9.1	0.41	- 3.11
11	944	6.7	0.31	- 3.75
12	945	7.7	0.35	- 3.75
13	949.5	8.3	0.38	- 4.38
14	950	6	0.27	- 5.02
15	949	5	0.23	- 5.02
16	953	7.3	0.33	- 5.65
17	957	10.3	0.47	- 6.91
18	914.5	9.5	0.43	
19	951.5	46.5	2.12	

DATA SHEET FOR TEST NO. 60X2.

Model discharge:	1.258 c.f.s.
Prototype discharge:	200,000 c.f.s.
Critical depth model:	0.367 ft.
Critical depth prototype:	22 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	959.5	54.5	2.48	+ 7.83
2	949.5	44.5	2.02	+ 3.75
3	946.5	41.5	1.89	+ 1.70
4	957	52	2.36	+ 0.34
5	952	36.3	1.65	- 1.21
6	948	32.3	1.42	- 1.21
7	942.5	21.2	0.96	- 1.84
8	942	15.2	0.69	- 2.48
9	940	13.2	0.60	- 2.48
10	942	9.6	0.44	- 3.11
11	944	6.7	0.30	- 3.75
12	945	7.7	0.35	- 3.75
13	949	7.8	0.35	- 4.38
14	950	6	0.27	- 5.02
15	948.5	4.5	0.20	- 5.02
16	953	7.3	0.33	- 5.65
17	956.5	9.8	0.45	- 6.91
18	927	22	1.00	
19	957	52	2.41	

DATA SHEET FOR TEST NO. 60X3.

Model discharge:	1.258 c.f.s.
Prototype discharge:	200,000 c.f.s.
Critical depth model:	0.367 ft.
Critical depth prototype:	22 ft.
Model scale:	1:60.
Remarks:	Friction blocks in place.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	965	60	2.73	+ 7.83
2	956	51	2.32	+ 3.75
3	954.5	49.5	2.25	+ 1.70
4	962	57	2.59	+ 0.34
5	957	41.3	1.88	- 1.21
6	954	38.3	1.74	- 1.21
7	950.5	29.2	1.33	- 1.84
8	948.5	21.7	0.99	- 2.48
9	948	21.2	0.96	- 2.48
10	944.5	12.1	0.55	- 3.11
11	944.5	7.2	0.33	- 3.75
12	945.5	8.2	0.37	- 3.75
13	949.5	8.3	0.38	- 4.38
14	950	6	0.27	- 5.02
15	948	4	0.18	- 5.02
16	953	7.3	0.33	- 5.65
17	957	10.3	0.47	- 6.91
18	939	34	1.54	
19	962.5	57.5	2.62	

DATA SHEET FOR TEST NO. 60XN1.

Model discharge:	1.102 c.f.s.
Prototype discharge:	175,000 c.f.s.
Critical depth model:	0.335 ft.
Critical depth prototype:	20.1 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	947.5	42.5	2.11	+ 8.56
2	936	31	1.54	+ 4.11
3	932	27	1.34	+ 1.86
4	946	41	2.04	+ 0.37
5	932.5	16.3	0.81	- 1.33
6	out			- 1.33
7	937.5	15.7	0.78	- 2.02
8	941.5	14.2	0.71	- 2.72
9	942	14.7	0.73	- 2.72
10	943	10.1	0.50	- 3.40
11	945.5	7.7	0.38	- 4.10
12	946	8.2	0.41	- 4.10
13	951.5	9.8	0.49	- 4.79
14	952	7.5	0.37	- 5.49
15	948.5	4.0	0.20	- 5.49
16	954	7.8	0.39	- 6.18
17	958.5	11.3	0.56	- 7.56
18				
19	952	47	2.34	

DATA SHEET FOR TEST NO. 60XN2.

Model discharge:	1.102 c.f.s.
Prototype discharge:	175,000 c.f.s.
Critical depth model:	0.335 ft.
Critical depth prototype:	20.1 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	955	50	2.49	+ 8.56
2	947.5	42.5	2.11	+ 4.11
3	944.5	39.5	1.96	+ 1.86
4	955	50	2.49	+ 0.37
5	942	25.8	1.28	- 1.33
6	out			- 1.33
7	941.5	19.7	0.98	- 2.02
8	942.5	15.2	0.76	- 2.72
9	942.5	15.2	0.76	- 2.72
10	943	10.1	0.50	- 3.40
11	945.5	7.7	0.38	- 4.10
12	946	8.2	0.41	- 4.10
13	951	9.3	0.46	- 4.79
14	952	7.5	0.37	- 5.49
15	948	3.5	0.17	- 5.49
16	954	7.8	0.39	- 6.18
17	958.5	11.3	0.56	- 7.56
18				
19	957.5	52.5	2.61	

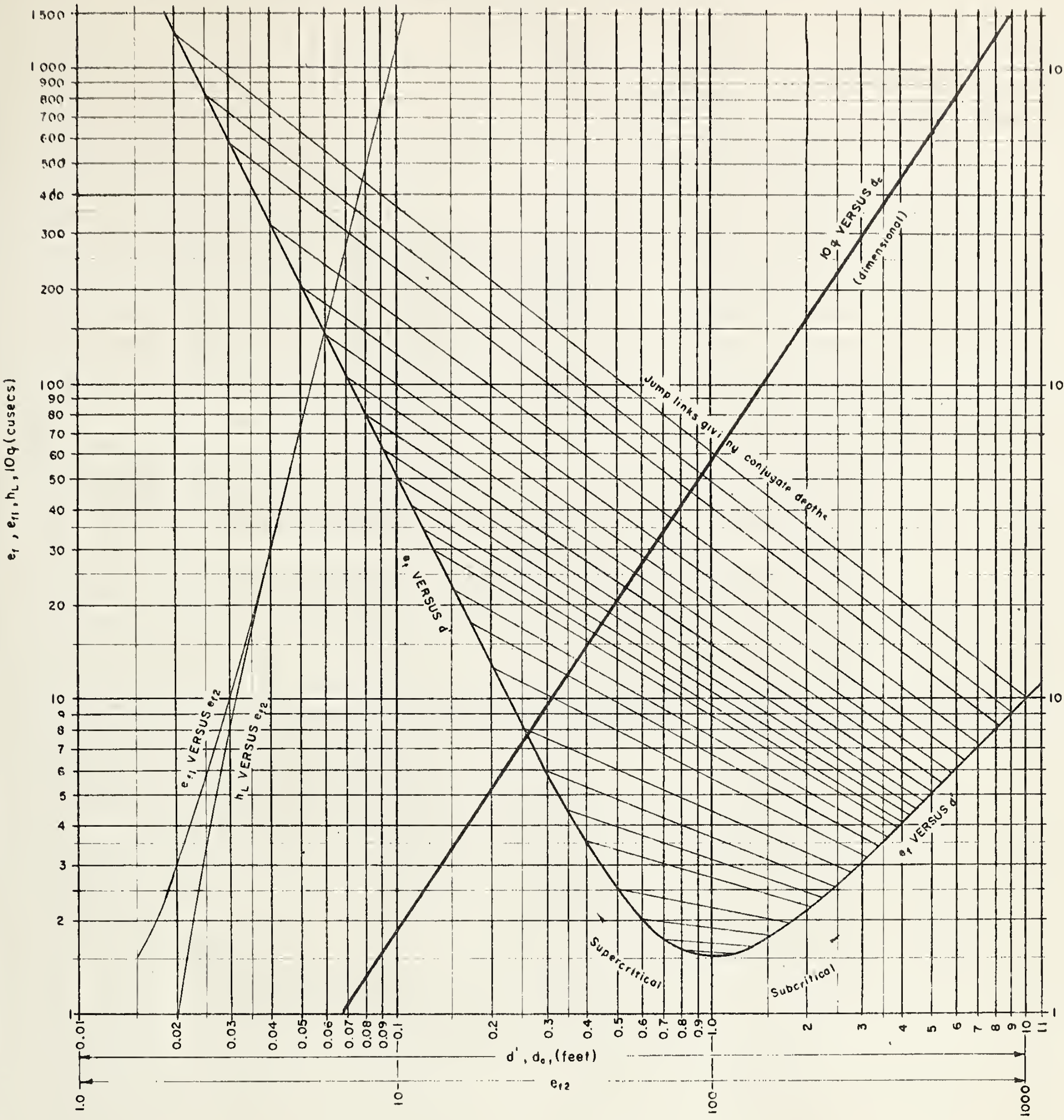
DATA SHEET FOR TEST NO. 60XN3.

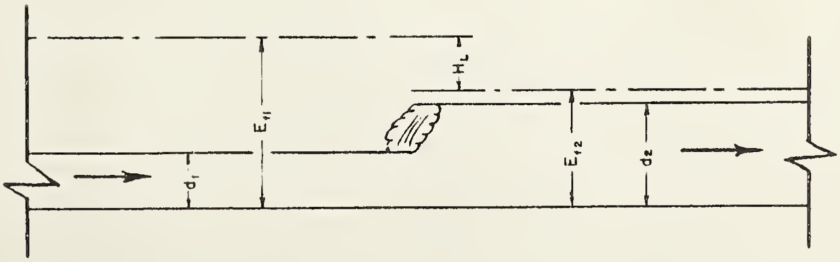
Model discharge:	1.102 c.f.s.
Prototype discharge:	175,000 c.f.s.
Critical depth model:	0.335 ft.
Critical depth prototype:	20.1 ft.
Model scale:	1:60.
Remarks:	No friction blocks.

Pressure point No.	Manometer reading in prototype feet.	Pressure head in prototype feet.	Non-dimensional pressure head.	Non-dimensional distance from hinge.
1	960	55	2.73	+ 8.56
2	955	50	2.49	+ 4.11
3	953	48	2.39	+ 1.86
4	960	55	2.73	+ 0.37
5	950.5	34.3	1.71	- 1.33
6	out			- 1.33
7	950	28.2	1.40	- 2.02
8	949.5	22.2	1.10	- 2.72
9	950	22.7	1.13	- 2.72
10	946.5	13.6	0.68	- 3.40
11	945.5	7.7	0.38	- 4.10
12	946.5	8.7	0.43	- 4.10
13	951.5	9.8	0.49	- 4.79
14	952	7.5	0.37	- 5.49
15	948	3.5	0.17	- 5.49
16	954	7.8	0.39	- 6.18
17	958.5	11.3	0.56	- 7.56
18				
19	962.5	57.5	2.86	

HYDRAULIC JUMP

Non-Dimensional Relations for Rectangular Channels





$e_f = d' + \frac{1}{2(d')^2}$

$h_L = \frac{H_L}{d_c}$

$d' = \frac{d}{d_c}$

$e_{f1} = \frac{E_{f1}}{d_c}$

$e_{f2} = \frac{E_{f2}}{d_c}$

$h_L = e_{f1} - e_{f2}$

$d_c = \sqrt[3]{\frac{q^2}{g}}$

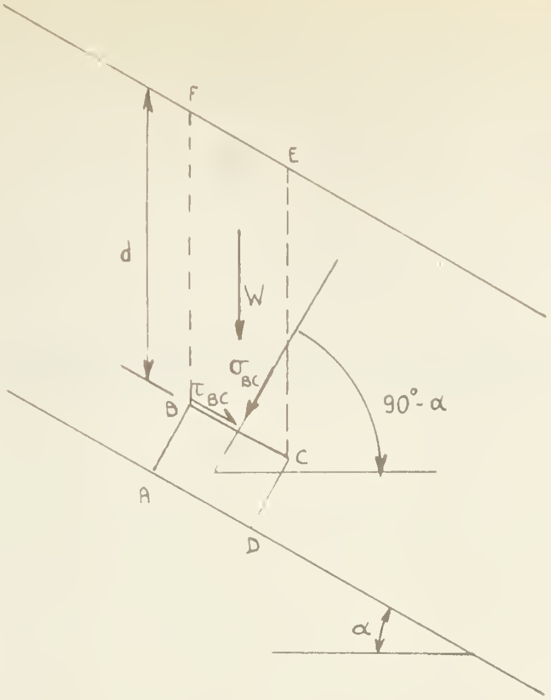
$E_f = d + \frac{q^2}{2gd^2}$

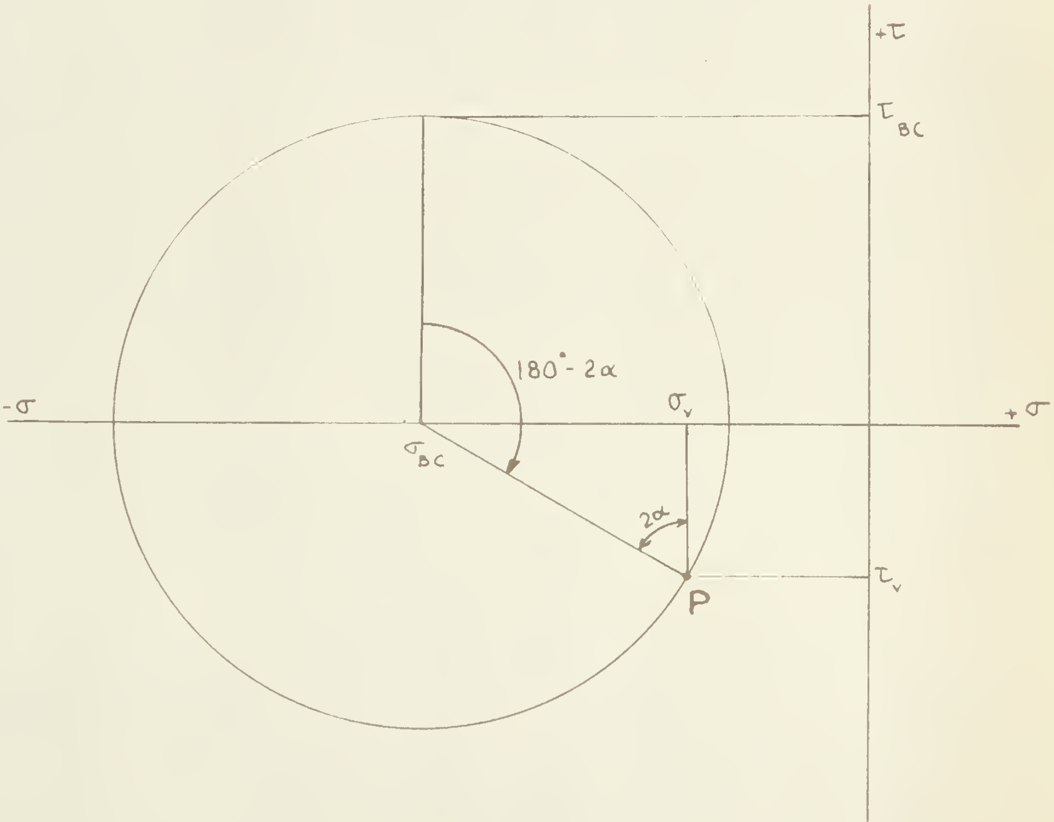
$d_1 d_2 (d_1 + d_2) = 2 d_c^3$

$H_L = \frac{(d_2 - d_1)^3}{4 d_1 d_2}$

PLATE I

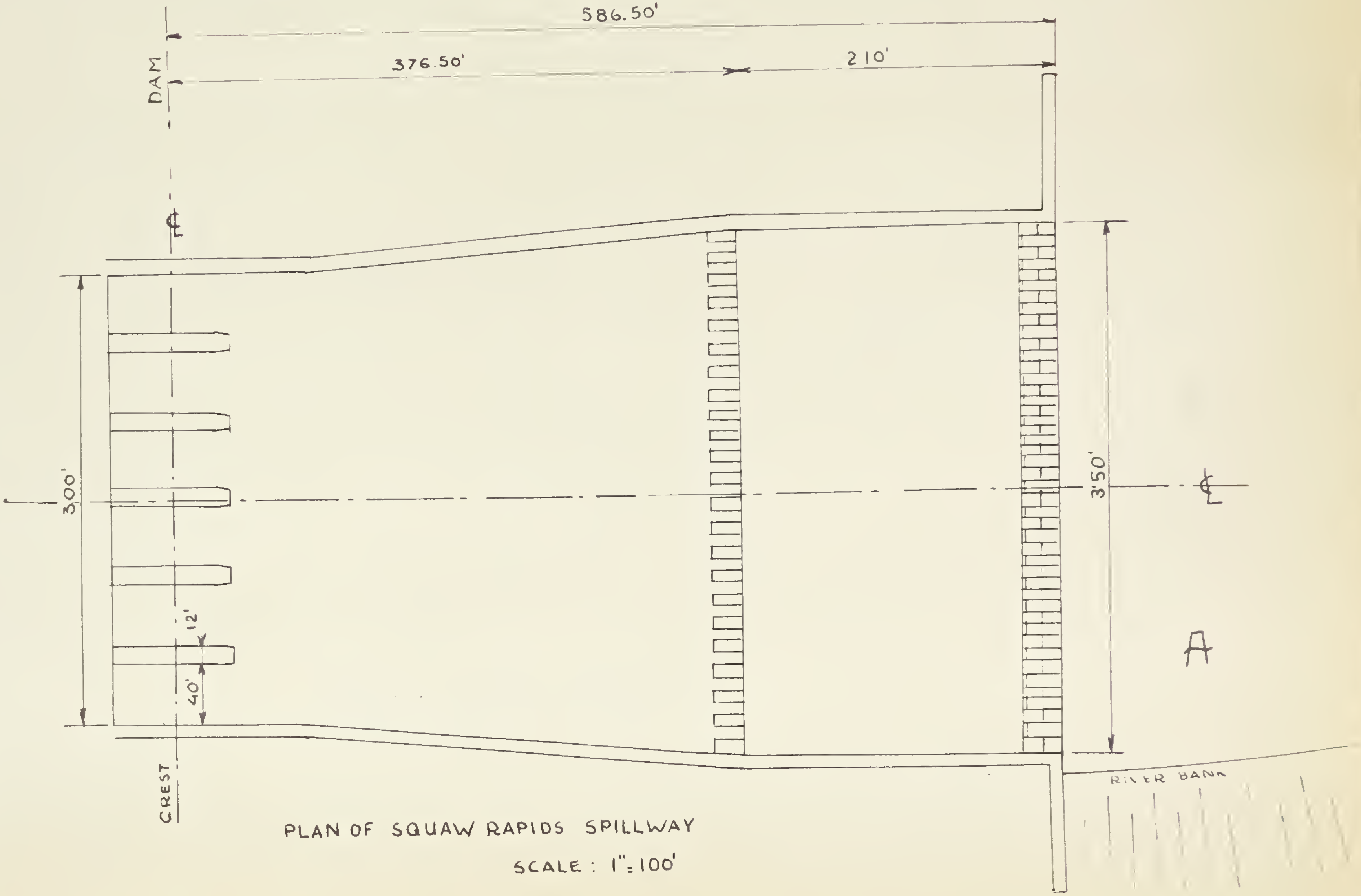
Drawn by. Hed.





MOHR'S CIRCLE

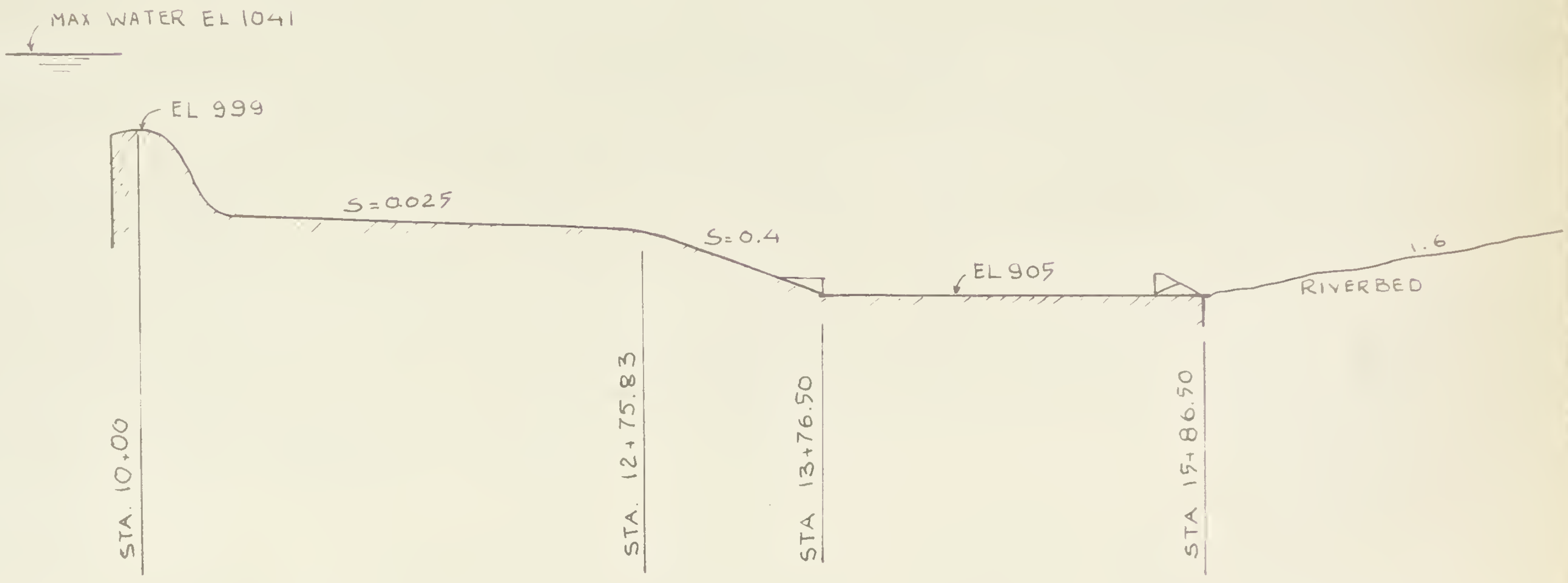
PLATE 2



PLAN OF SQUAW RAPIDS SPILLWAY

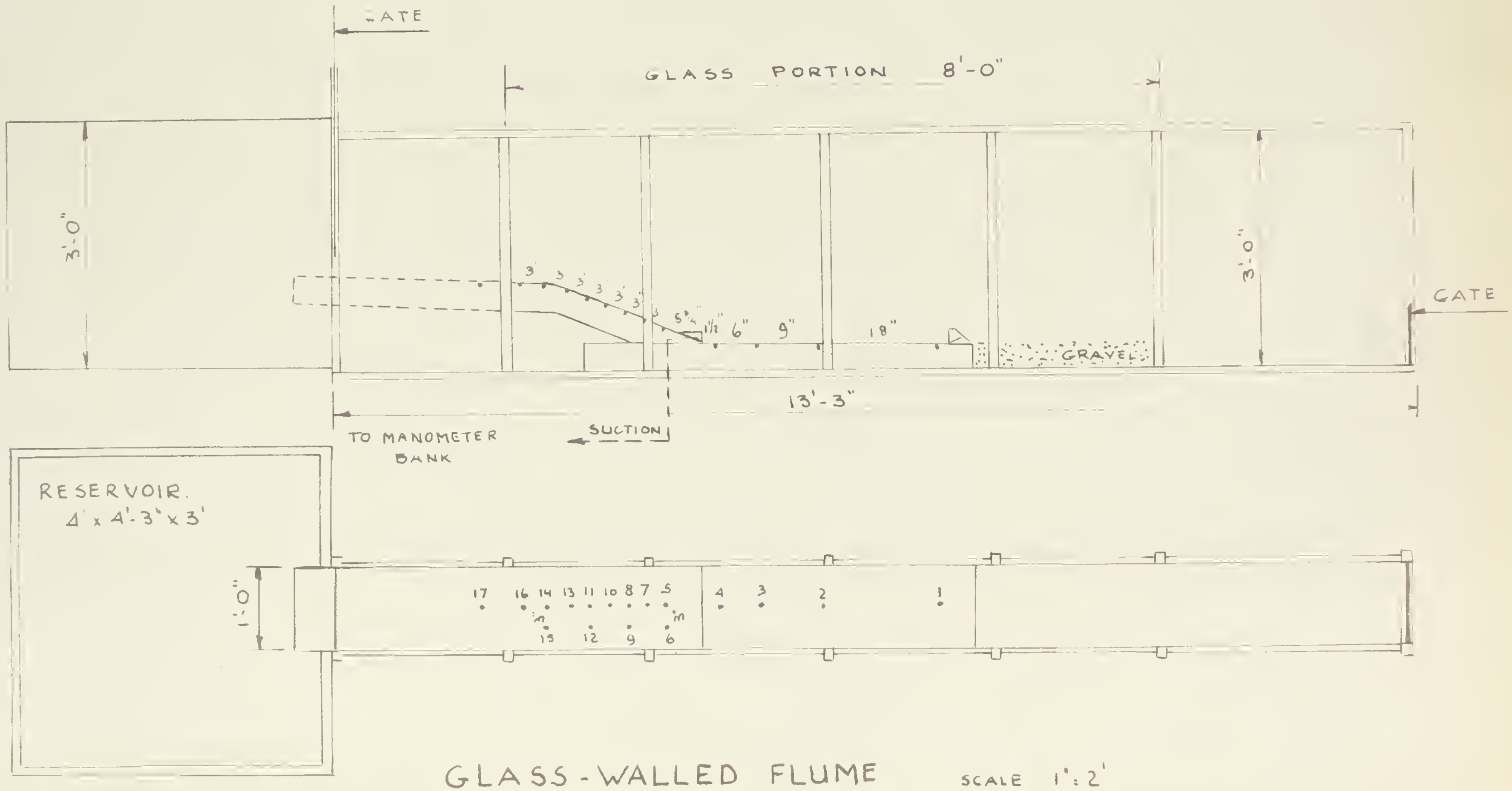
SCALE : 1" = 100'

PLATE 3



SQUAW RAPIDS SPILLWAY
LONGITUDINAL SECTION
SCALE 1"=100'

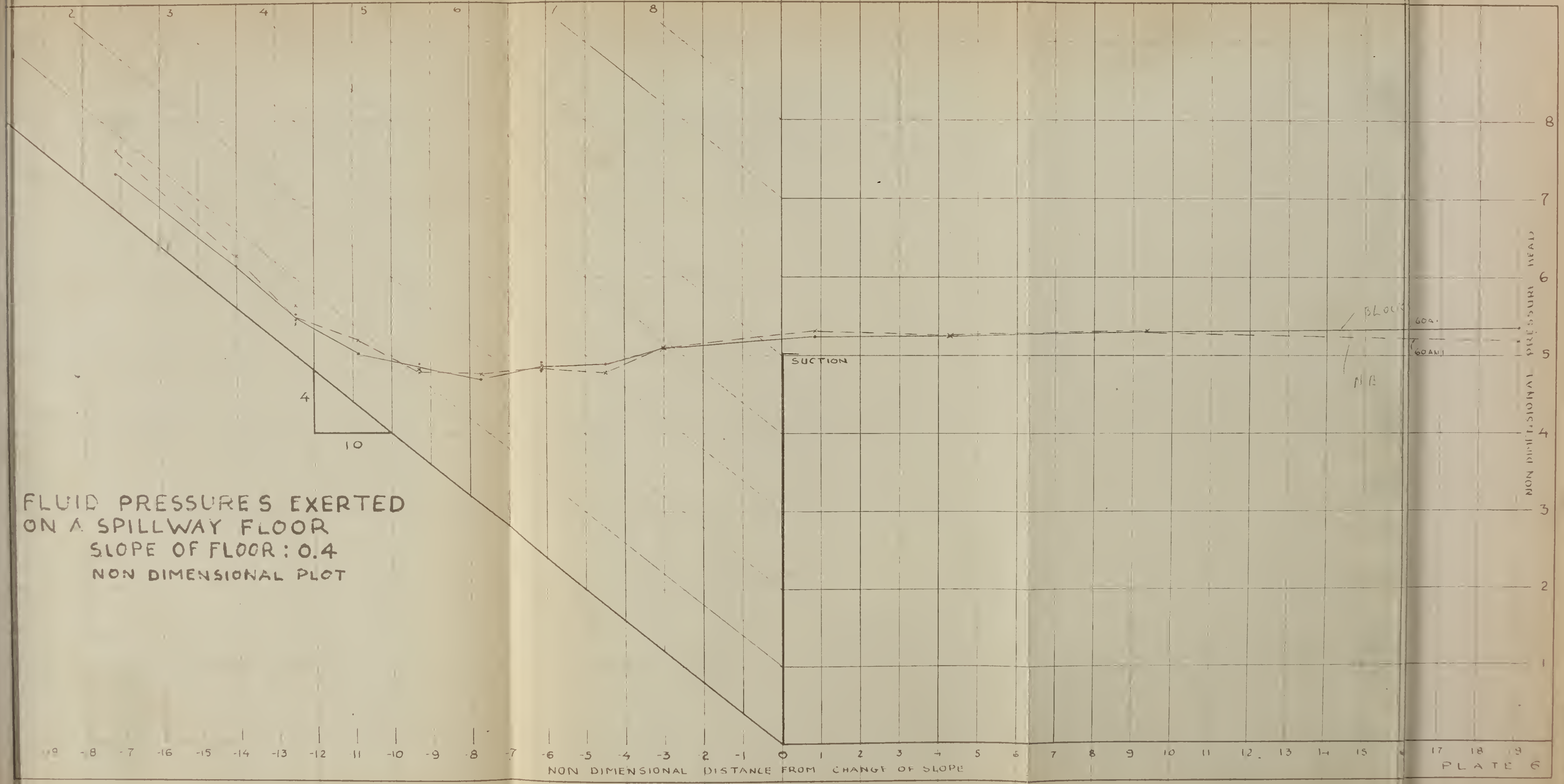
PLATE 4



GLASS-WALLED FLUME scale 1':2'

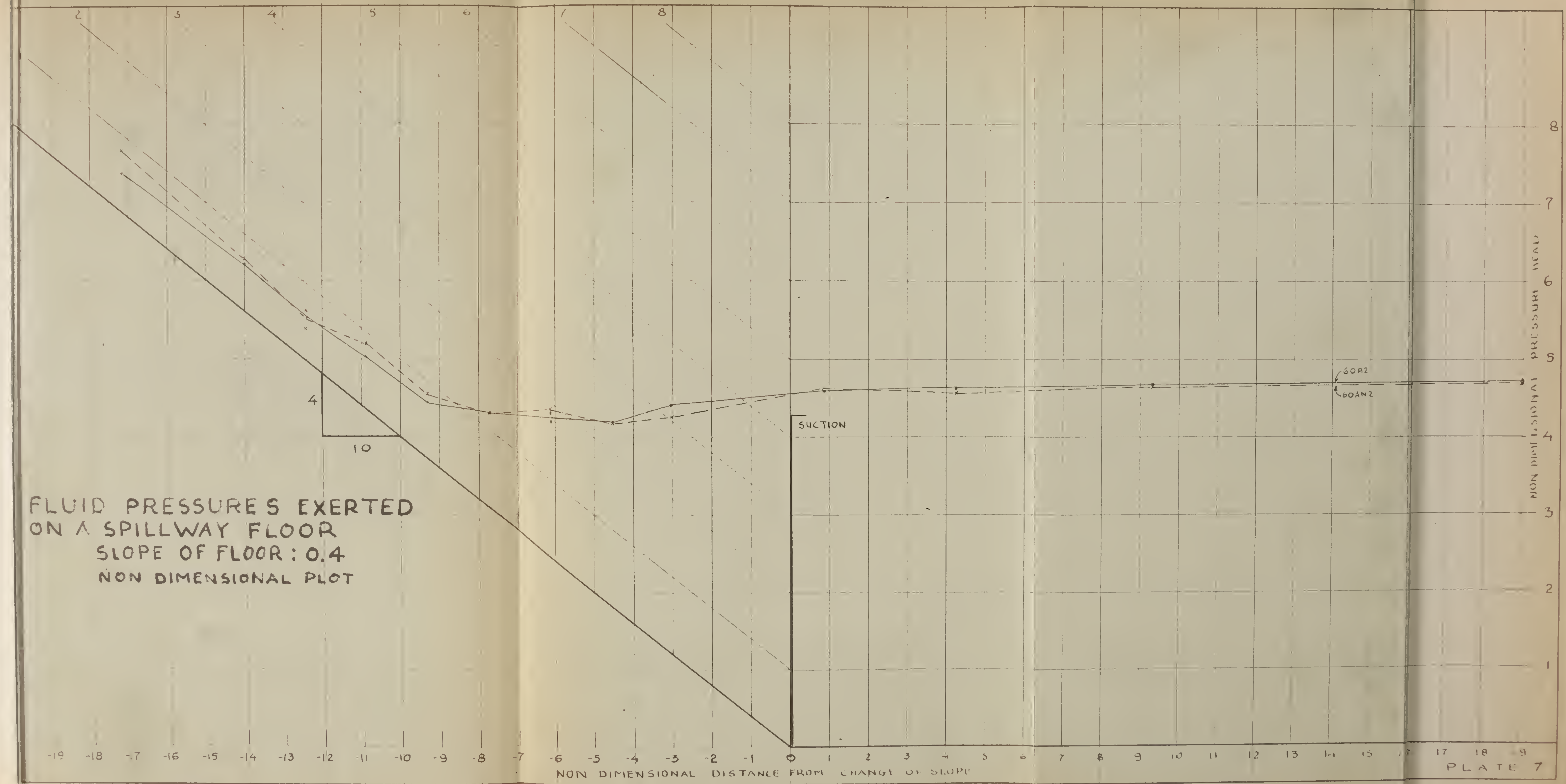
LOCATION OF PRESSURE MEASURING POINTS

PLATE 5



FLUID PRESSURES EXERTED
ON A SPILLWAY FLOOR
SLOPE OF FLOOR : 0.4
NON DIMENSIONAL PLOT

PLATE 6

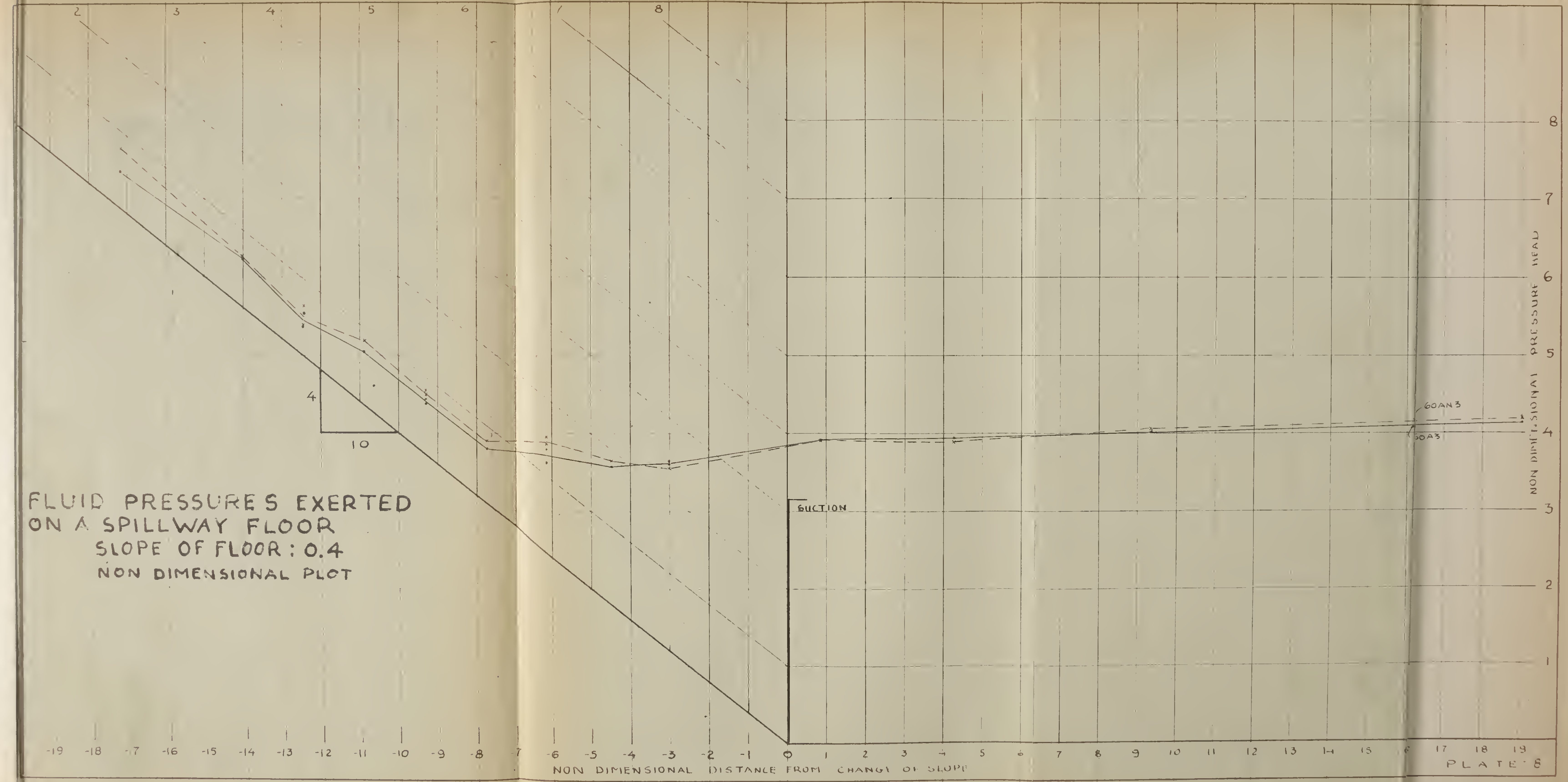


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE 7

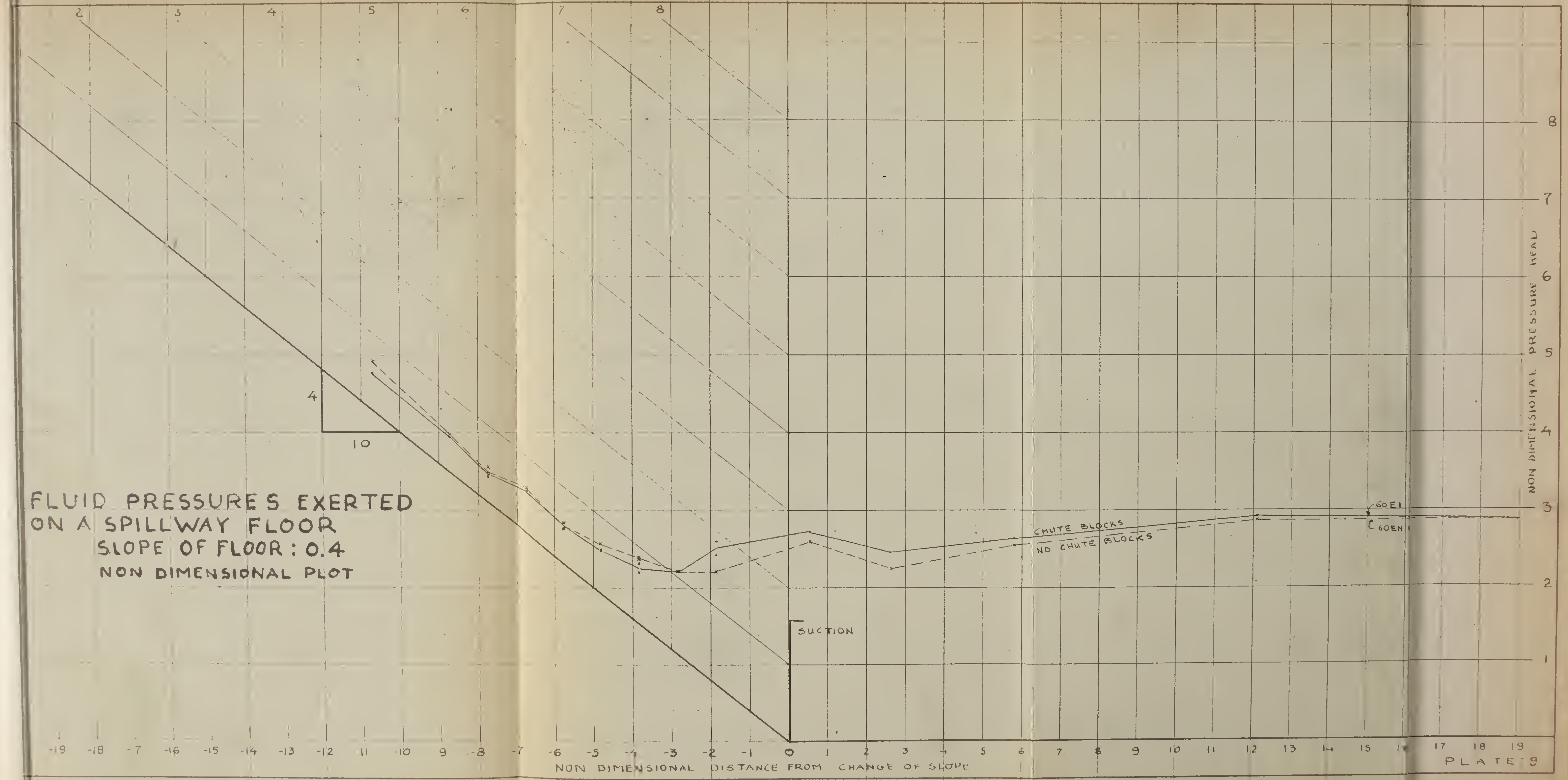


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

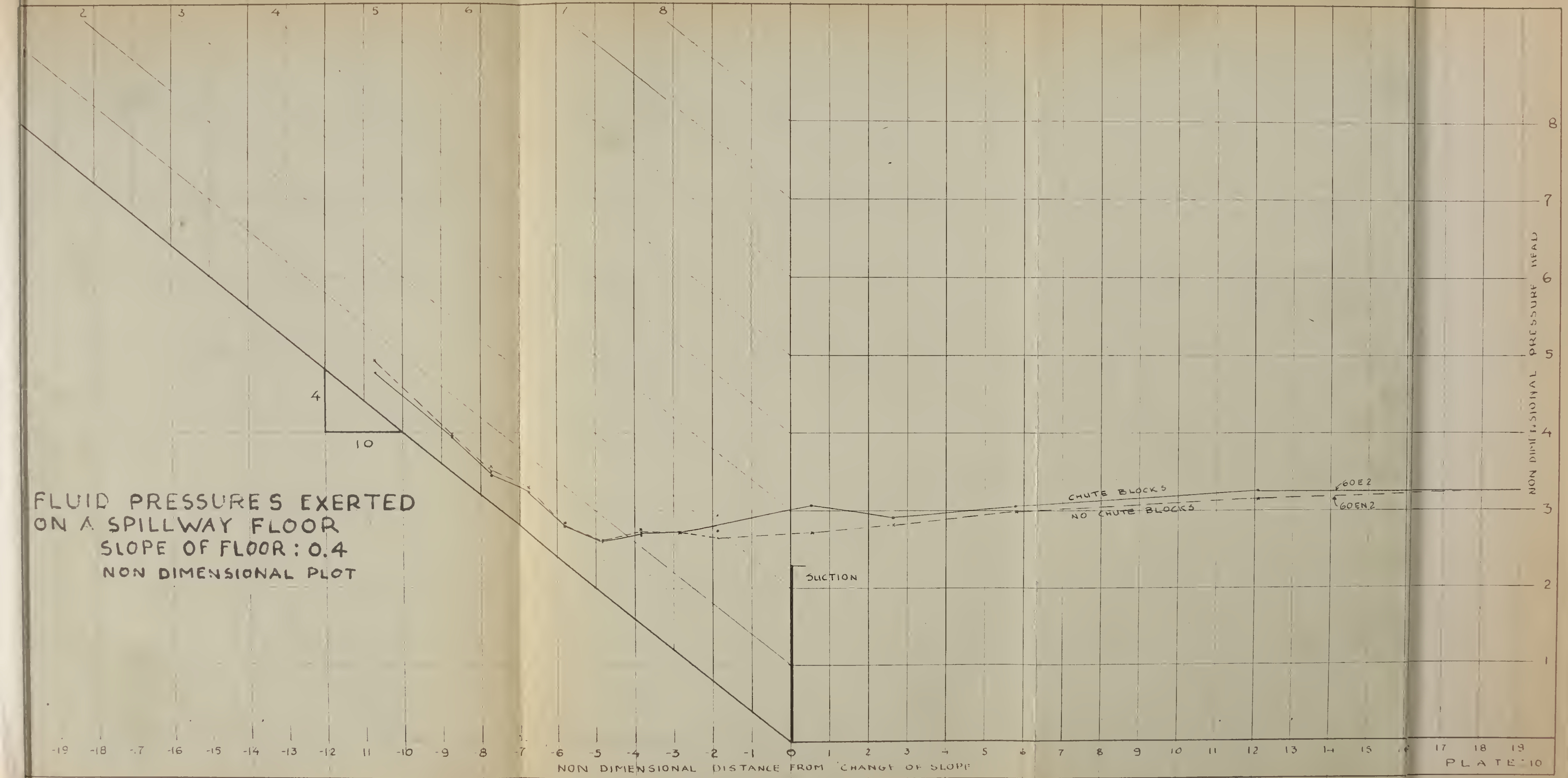
PLATE 8


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE 9

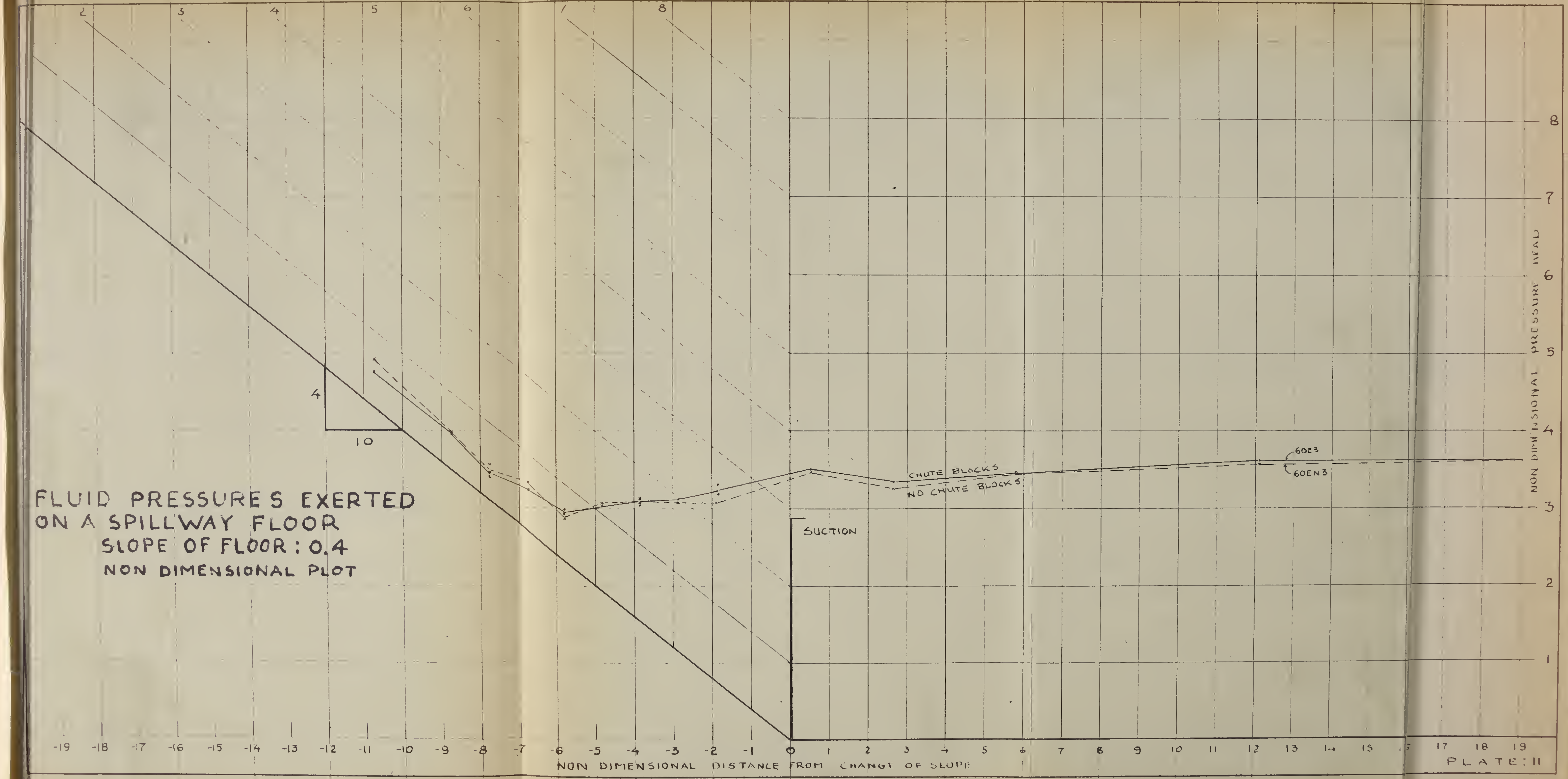


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE 10


FLUID PRESSURES EXERTED
ON A SPILLWAY FLOOR
SLOPE OF FLOOR : 0.4
NON DIMENSIONAL PLOT
2
3
4
5
6
7
8
4
10
SUCTION
CHUTE BLOCKS
NO CHUTE BLOCKS
60E3
60EN3
NON DIMENSIONAL PRESSURE HEAD
1
2
3
4
5
6
7
8
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
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5
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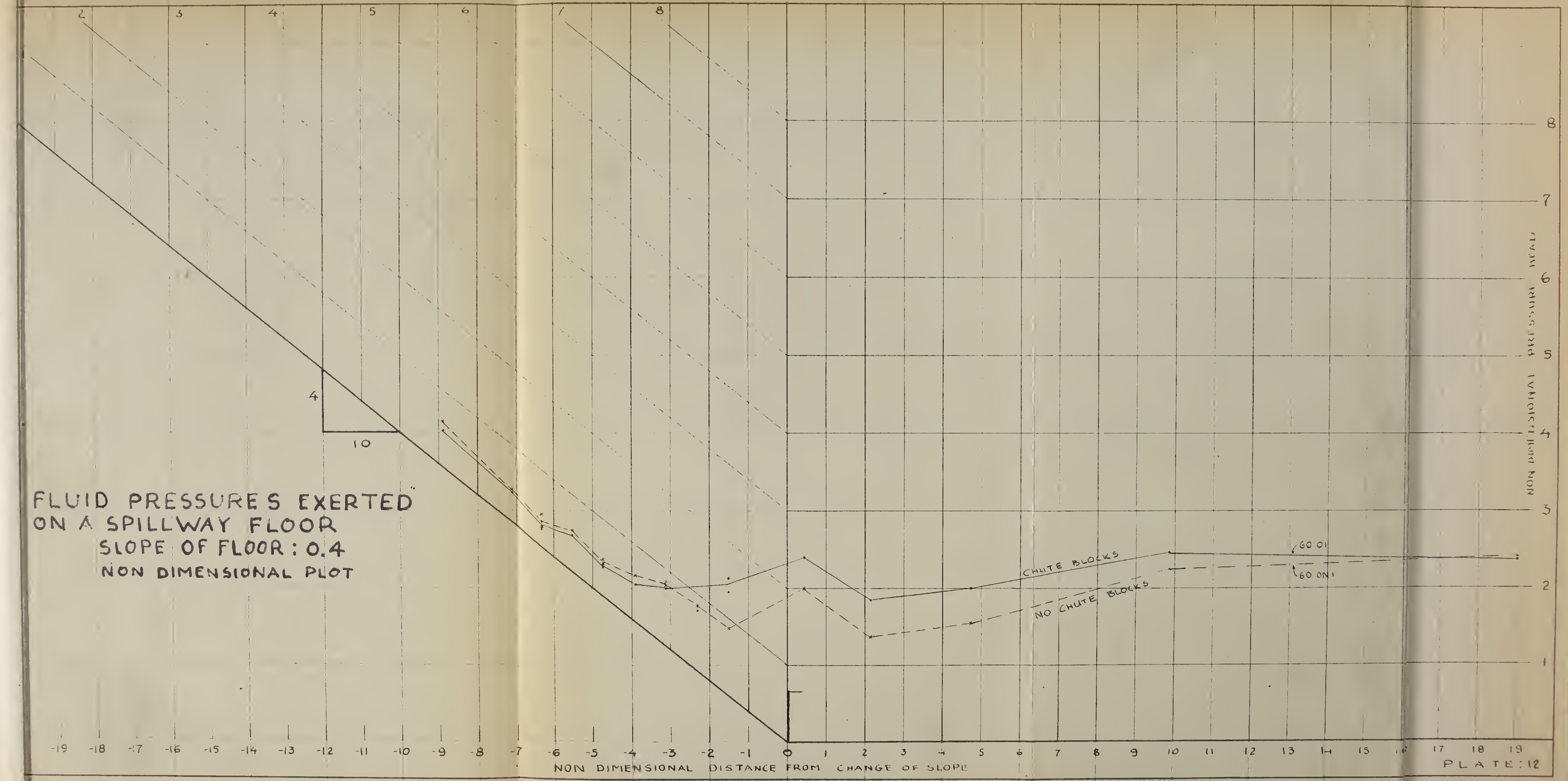
19
NON DIMENSIONAL DISTANCE FROM CHANGE OF SLOPE

PLATE: II

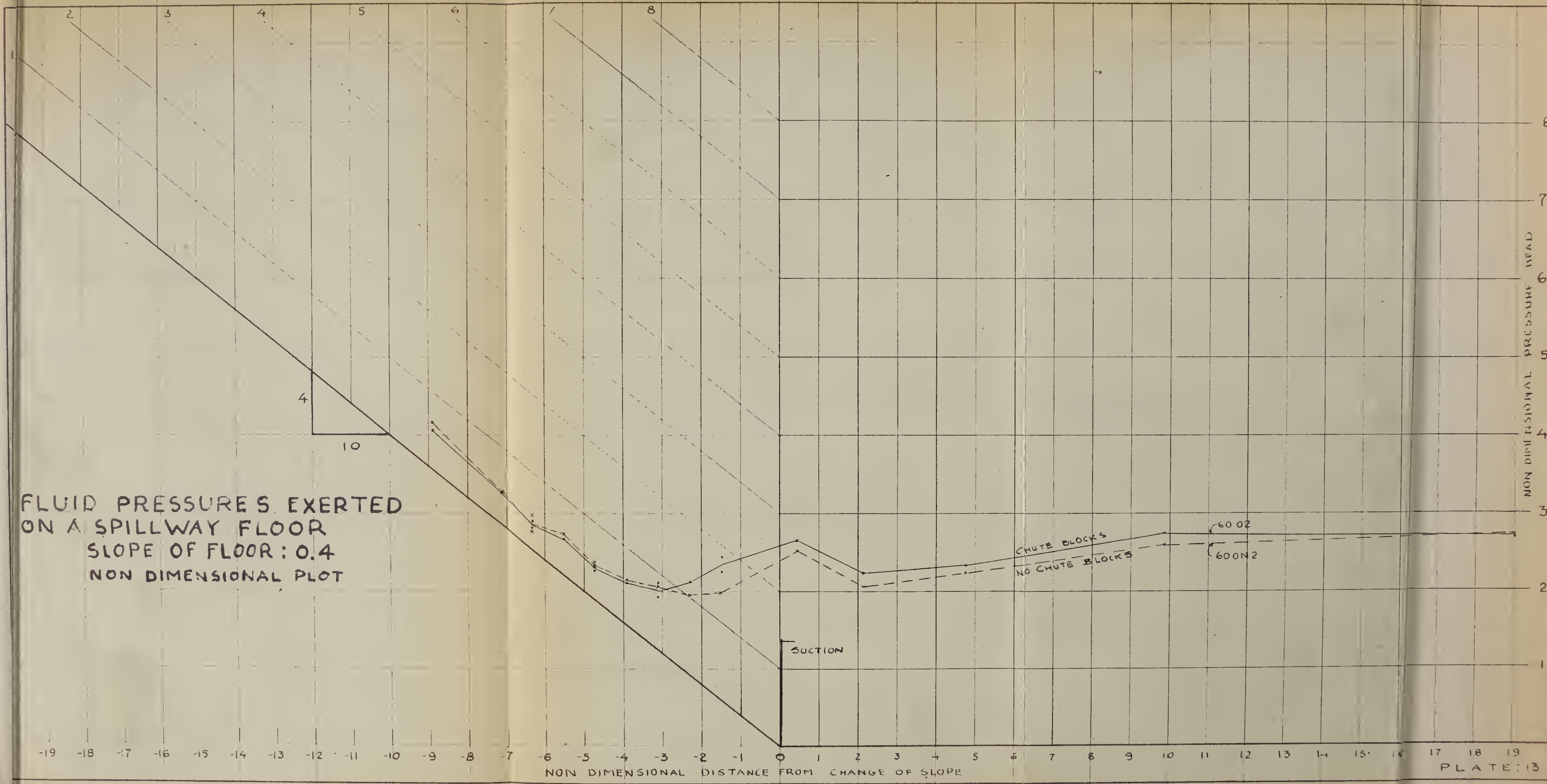


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE: 12

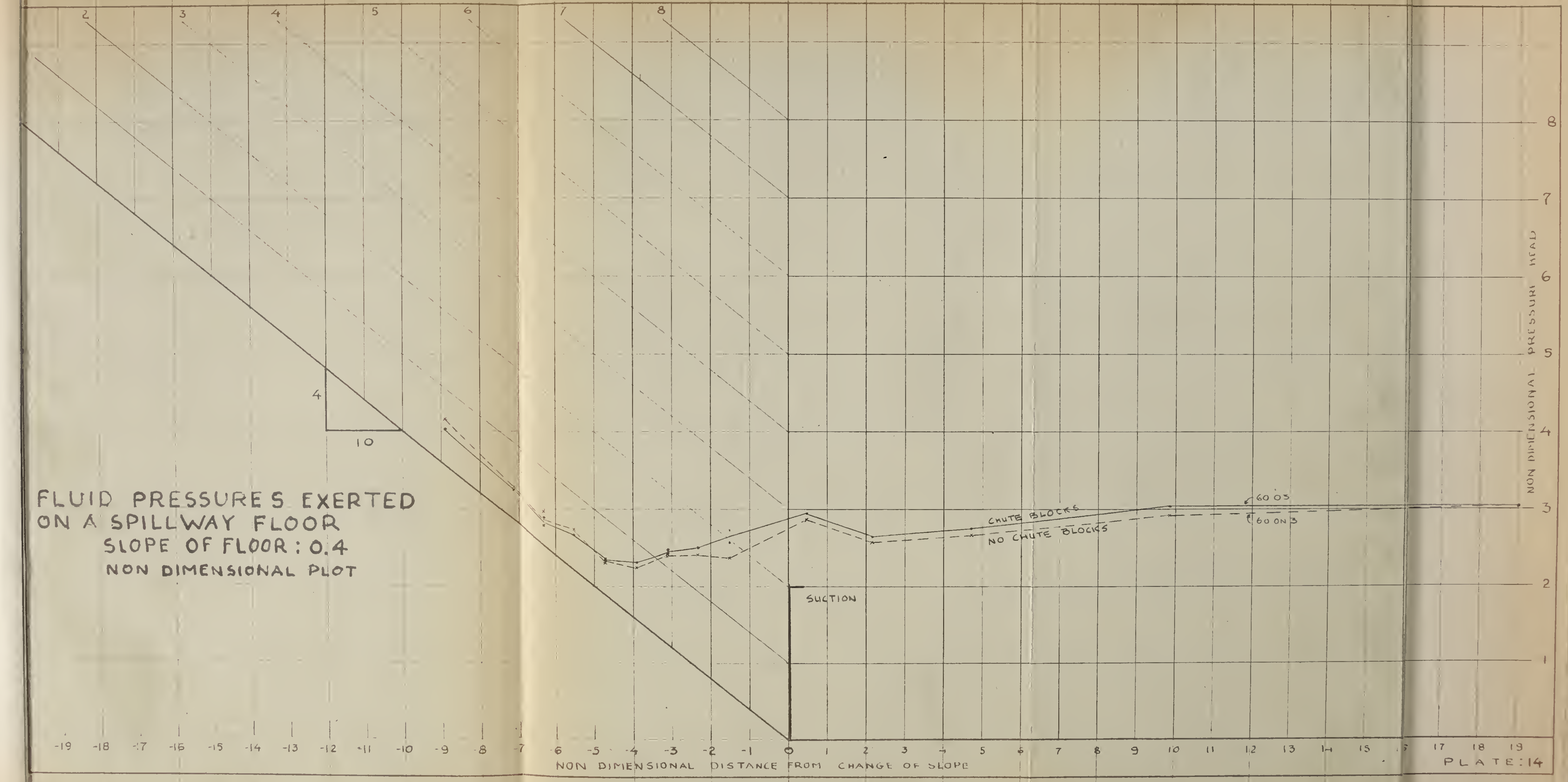


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE: 13

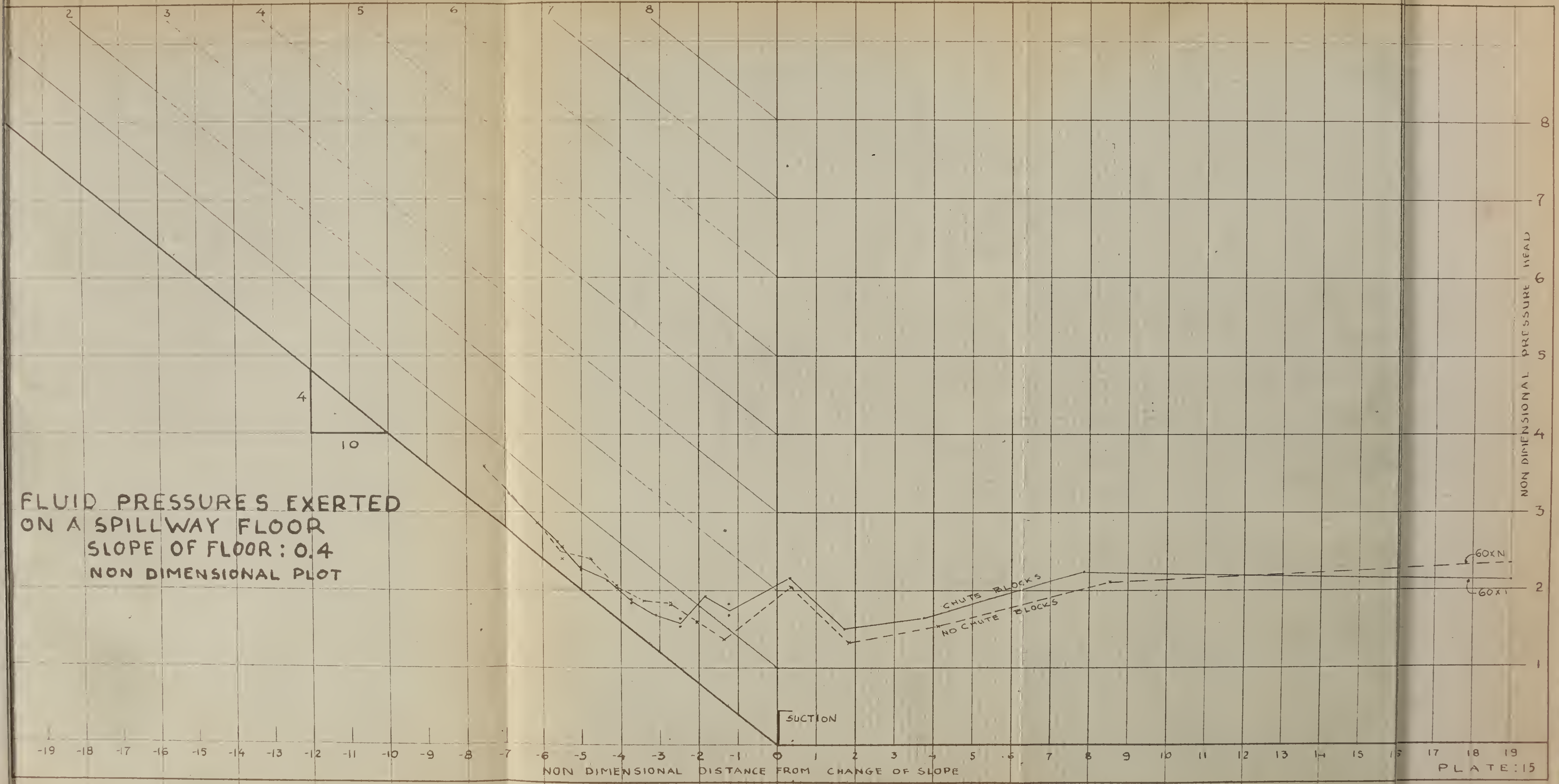


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE:14

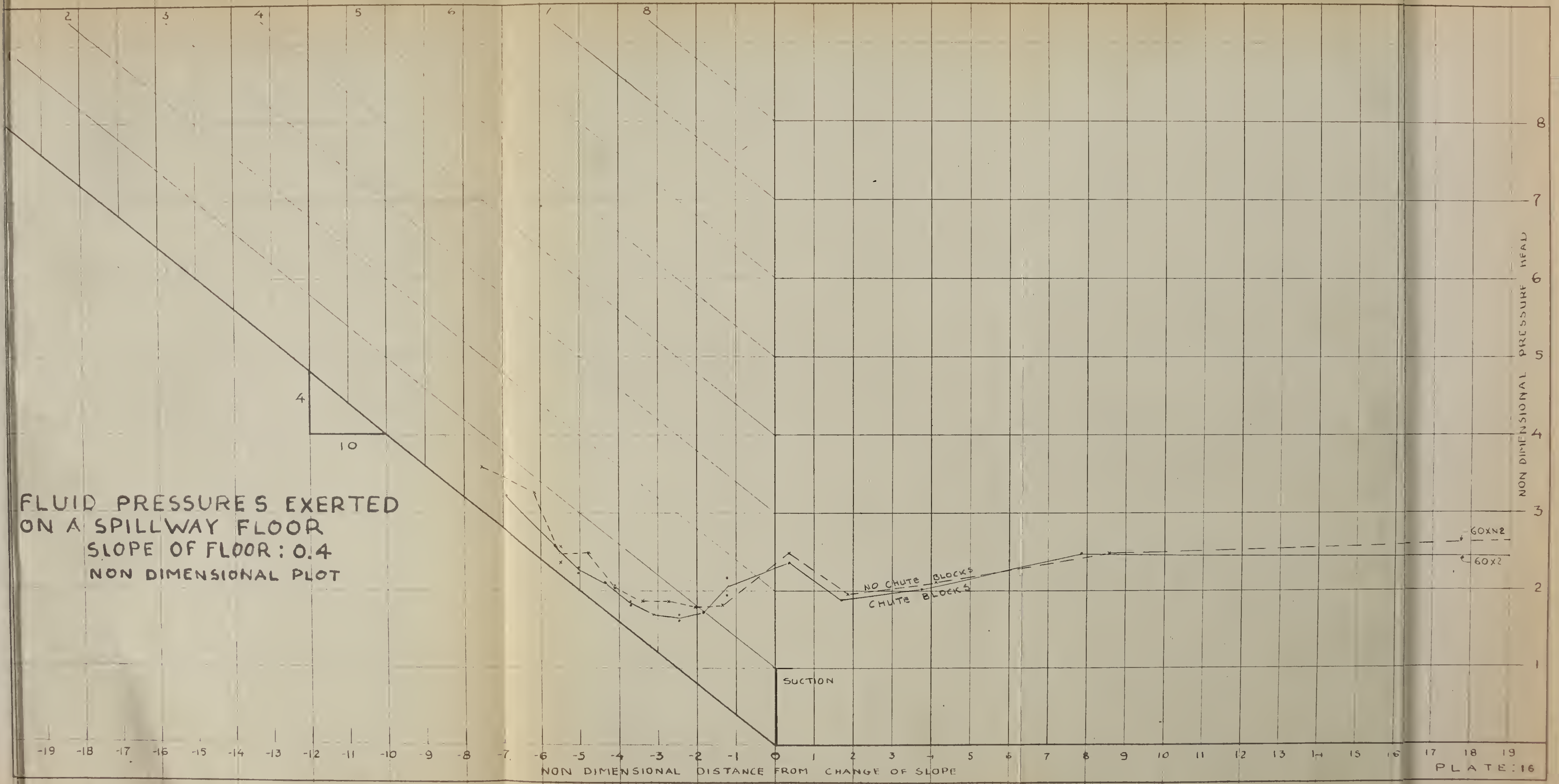


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

PLATE: 15

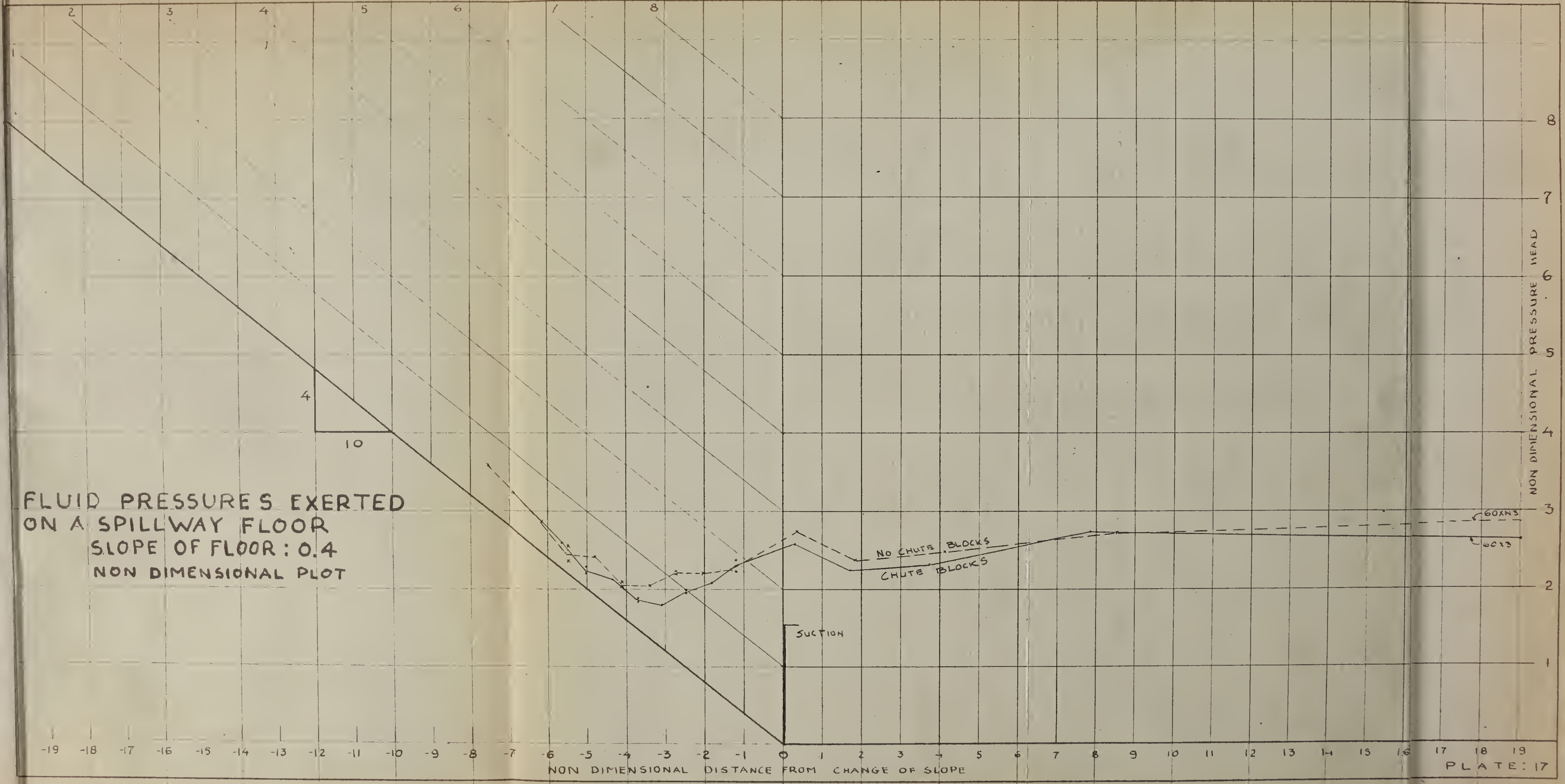


FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR

SLOPE OF FLOOR : 0.4

NON DIMENSIONAL PLOT

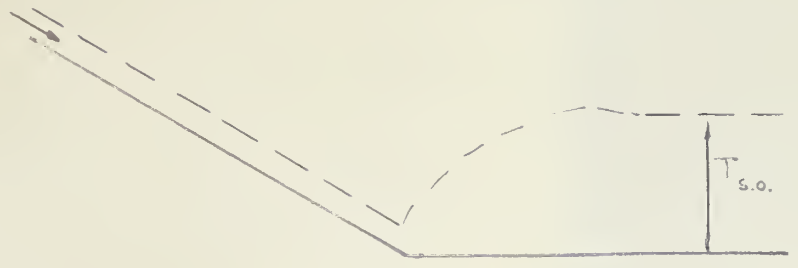
PLATE: 16



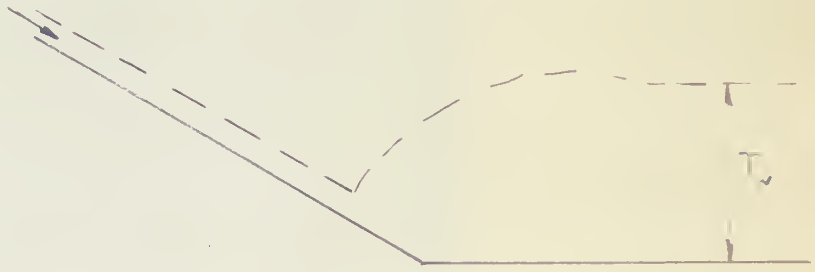
FLUID PRESSURES EXERTED ON A SPILLWAY FLOOR
SLOPE OF FLOOR: 0.4
NON DIMENSIONAL PLOT

PLATE: 17

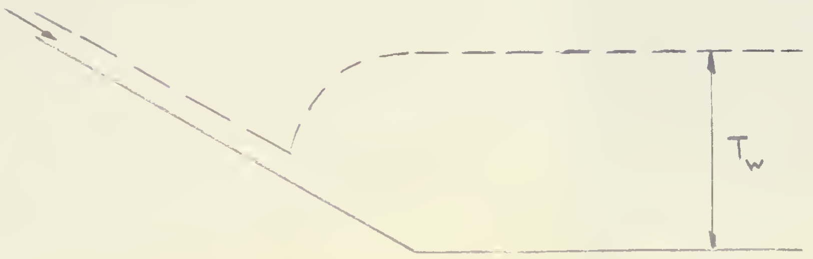
CLASSIFICATION OF JUMPS SLOPING FLOOR



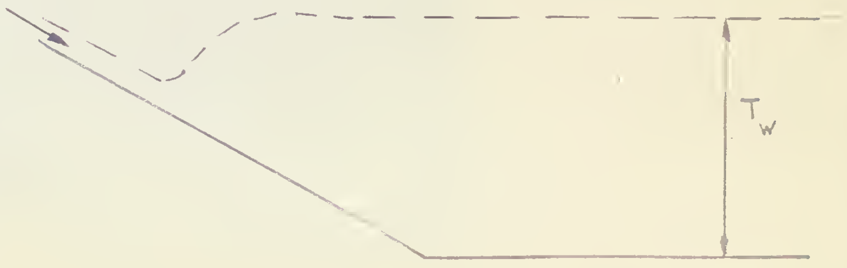
CASE "A"



CASE "B"

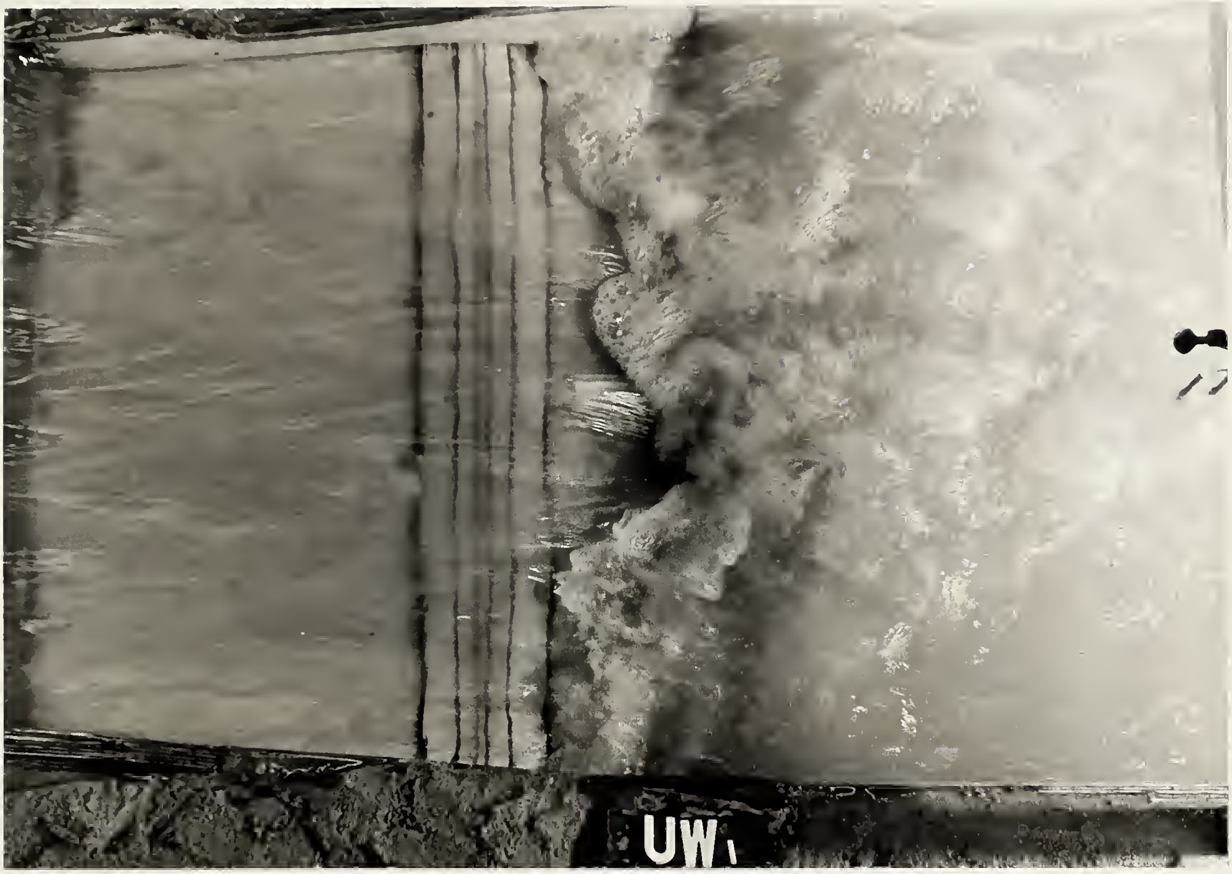


CASE "C"



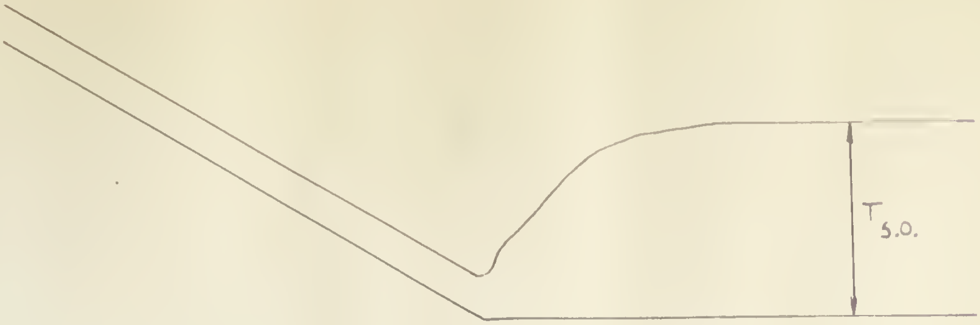
CASE "D"

PLATE 18

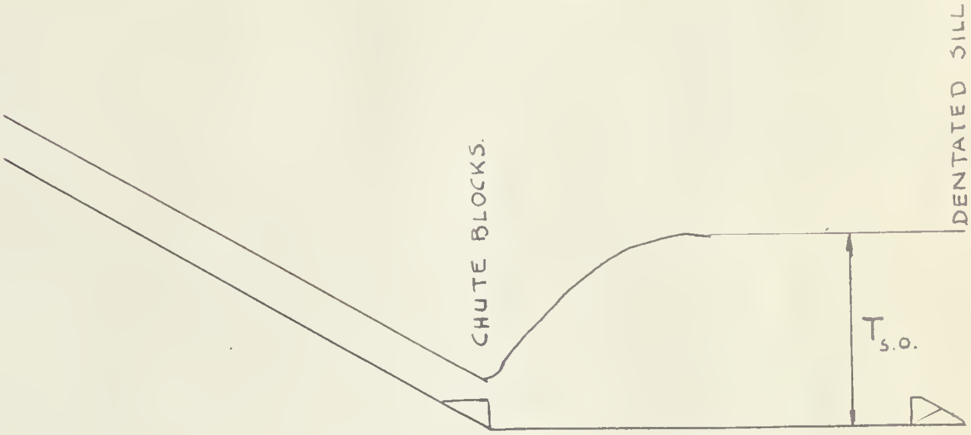


Hydraulic jump in three-dimensional model.

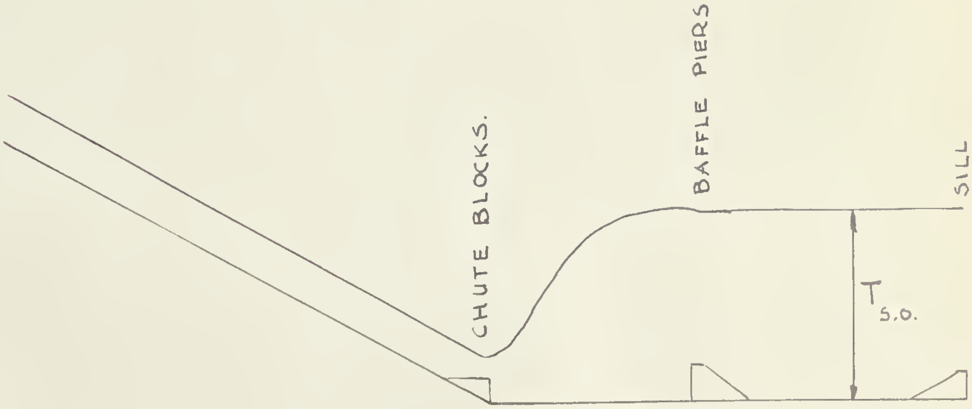
(Model scale 1:150)



BASIN I



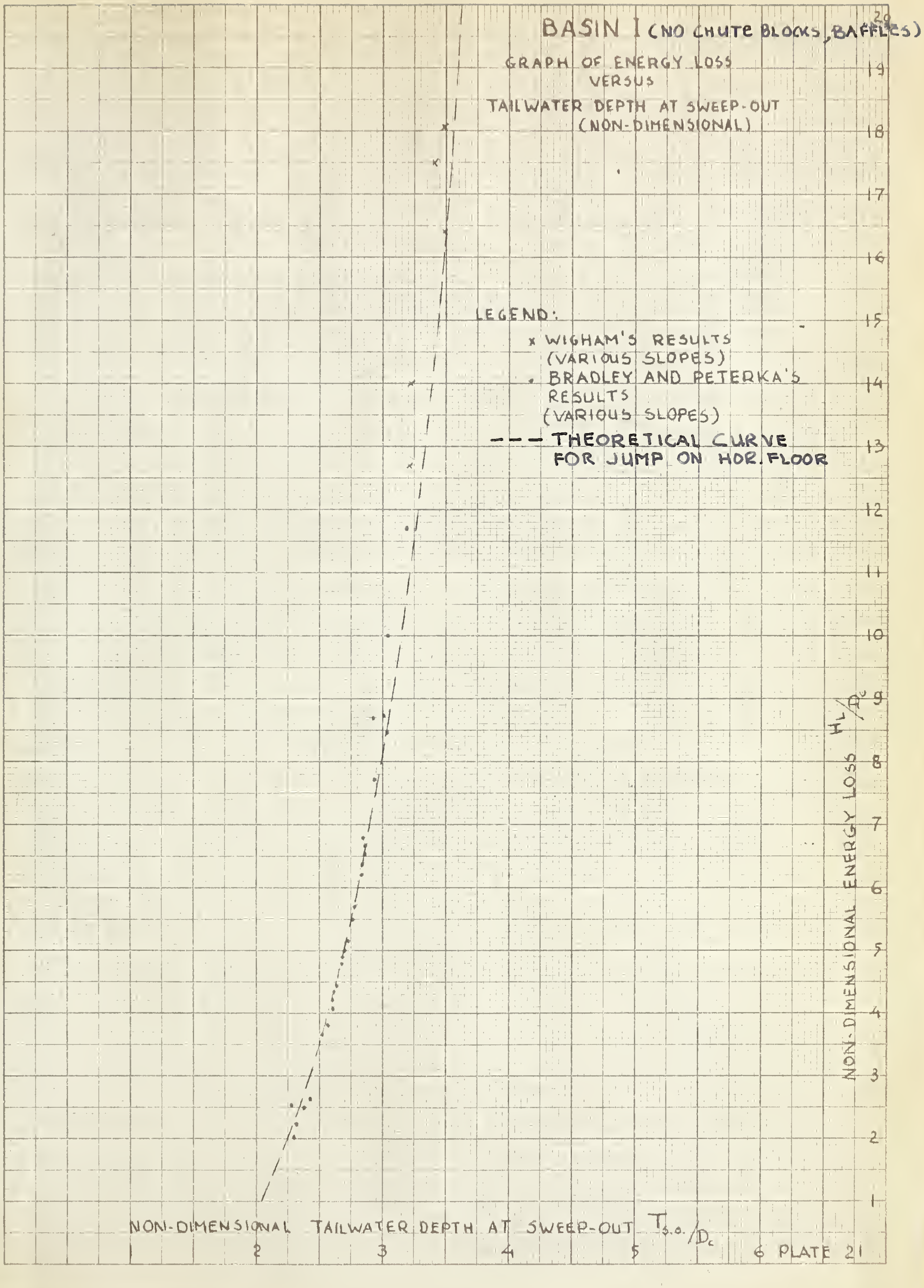
BASIN II



BASIN III

TYPES OF STILLING BASINS

PLATE 20



BASIN I (NO CHUTE BLOCKS, BAFFLES)

GRAPH OF ENERGY LOSS
VERSUS
TAILWATER DEPTH AT SWEEP-OUT
(NON-DIMENSIONAL)

PLATE 21

BASIN II (WITH CHUTE BLOCKS)

GRAPH OF ENERGY LOSS
VERSUS
TAILWATER DEPTH AT SWEEP-OUT
(NON-DIMENSIONAL)

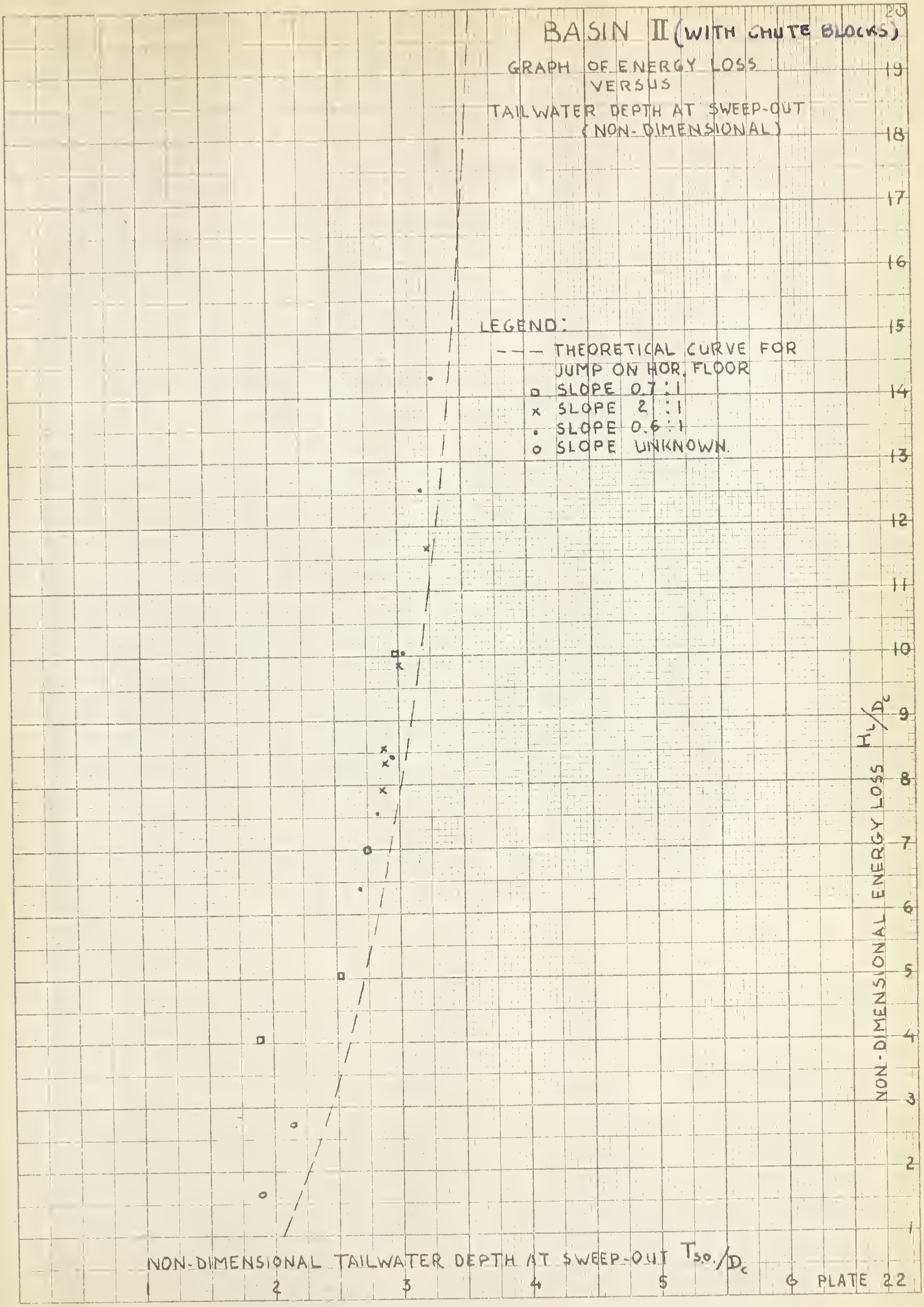


PLATE 22

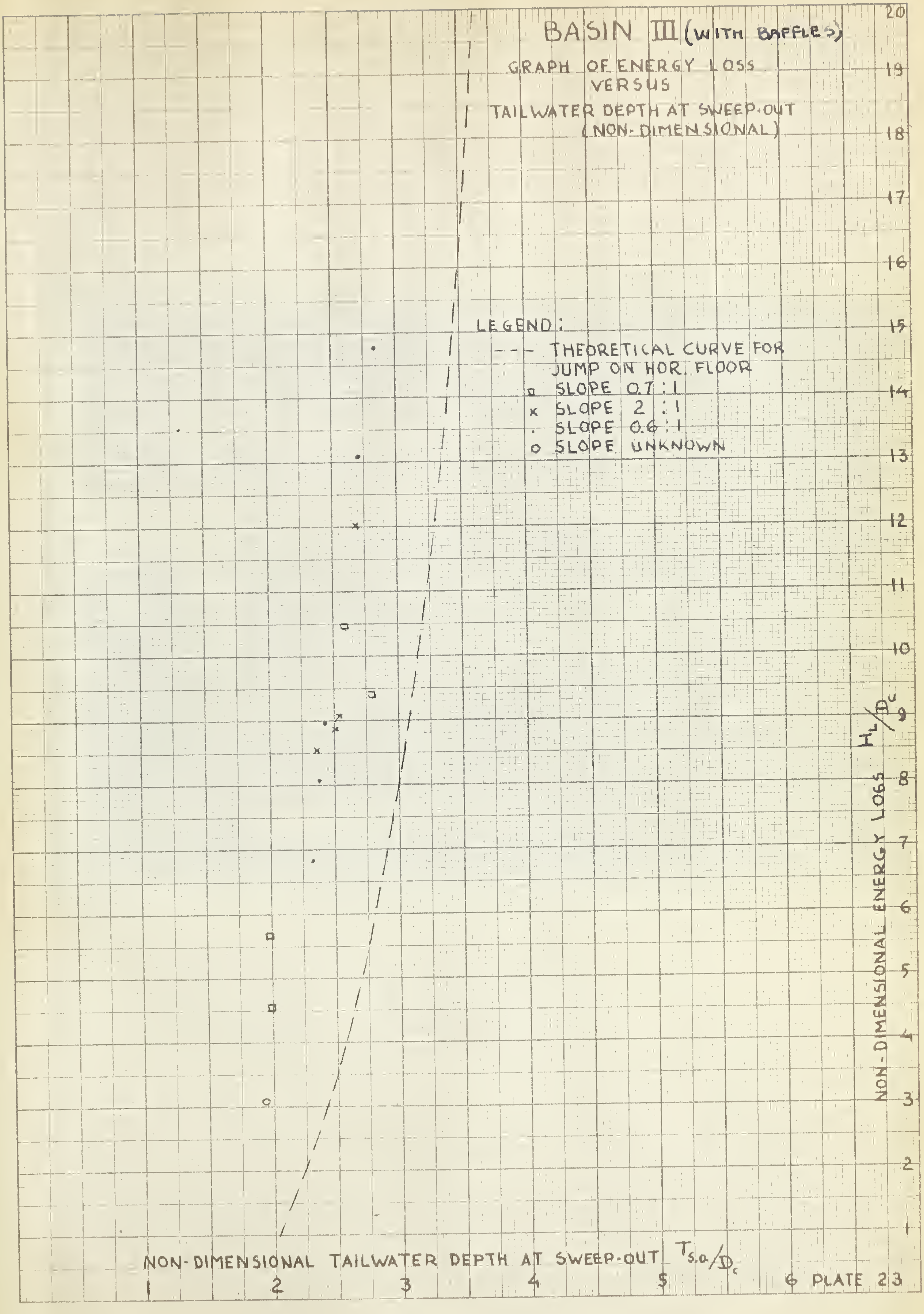
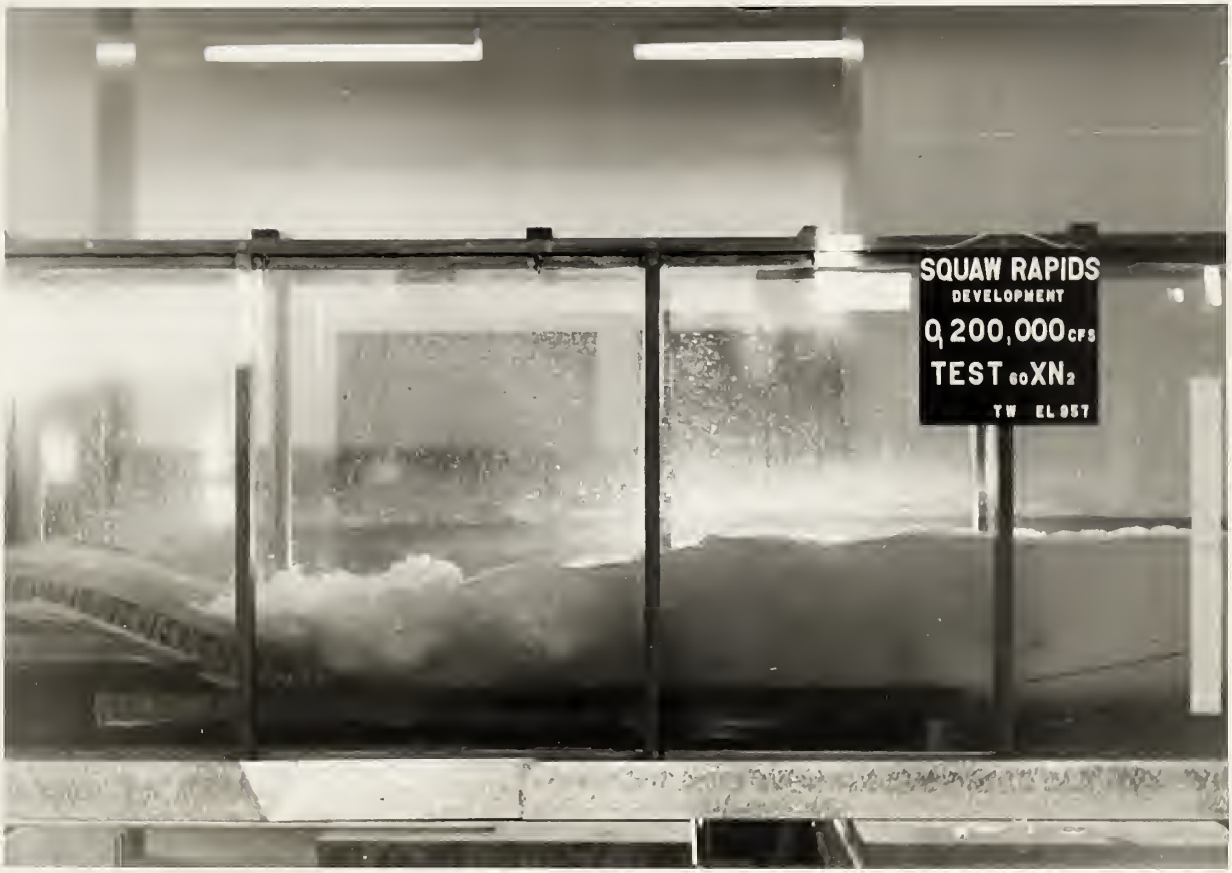
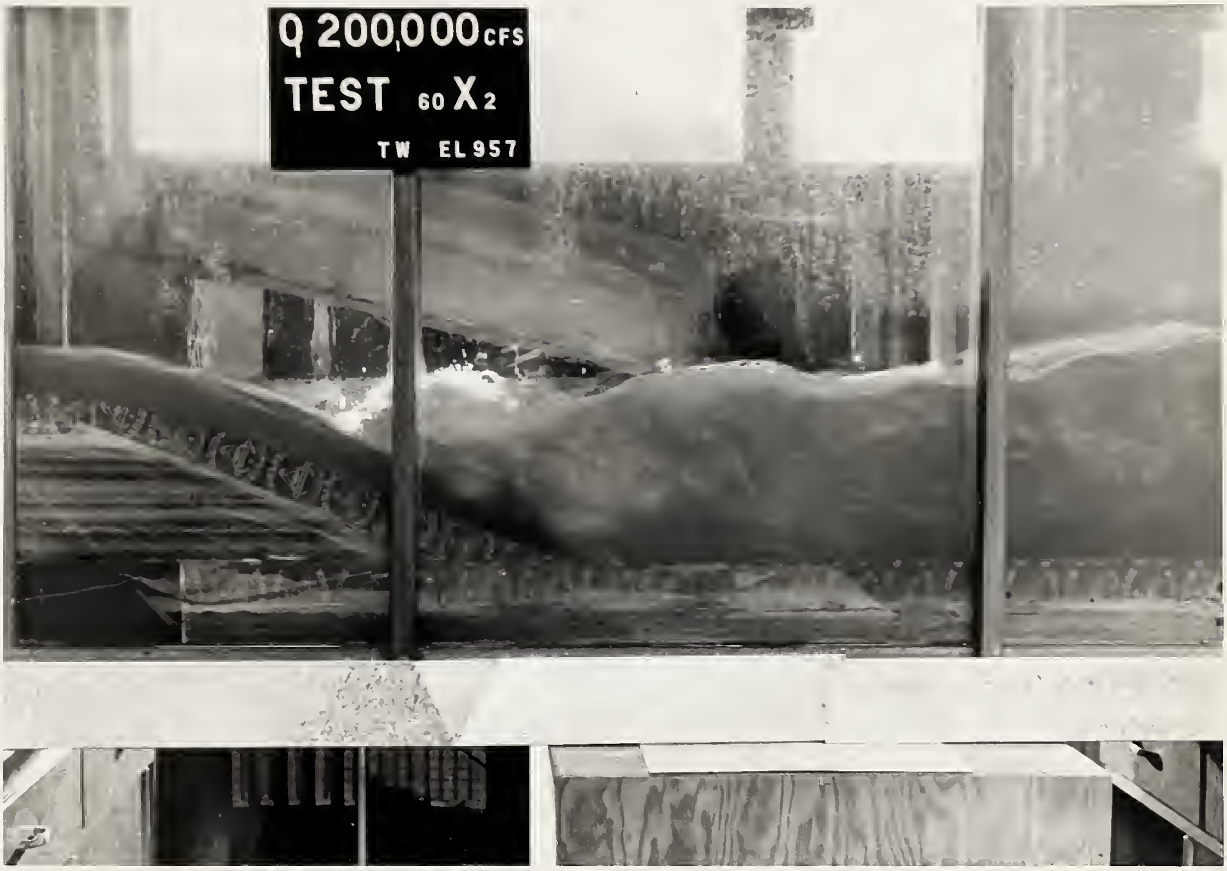

BASIN III (WITH BAFFLES)
GRAPH OF ENERGY LOSS
VERSUS
TAILWATER DEPTH AT SWEEP-OUT
(NON-DIMENSIONAL)
LEGEND:
--- THEORETICAL CURVE FOR JUMP ON HOR. FLOOR
□ SLOPE 0.7 : 1
x SLOPE 2 : 1
. SLOPE 0.6 : 1
o SLOPE UNKNOWN
NON-DIMENSIONAL ENERGY LOSS H_L/D_c
NON-DIMENSIONAL TAILWATER DEPTH AT SWEEP-OUT $T_{s.o.}/D_c$
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

PLATE 23



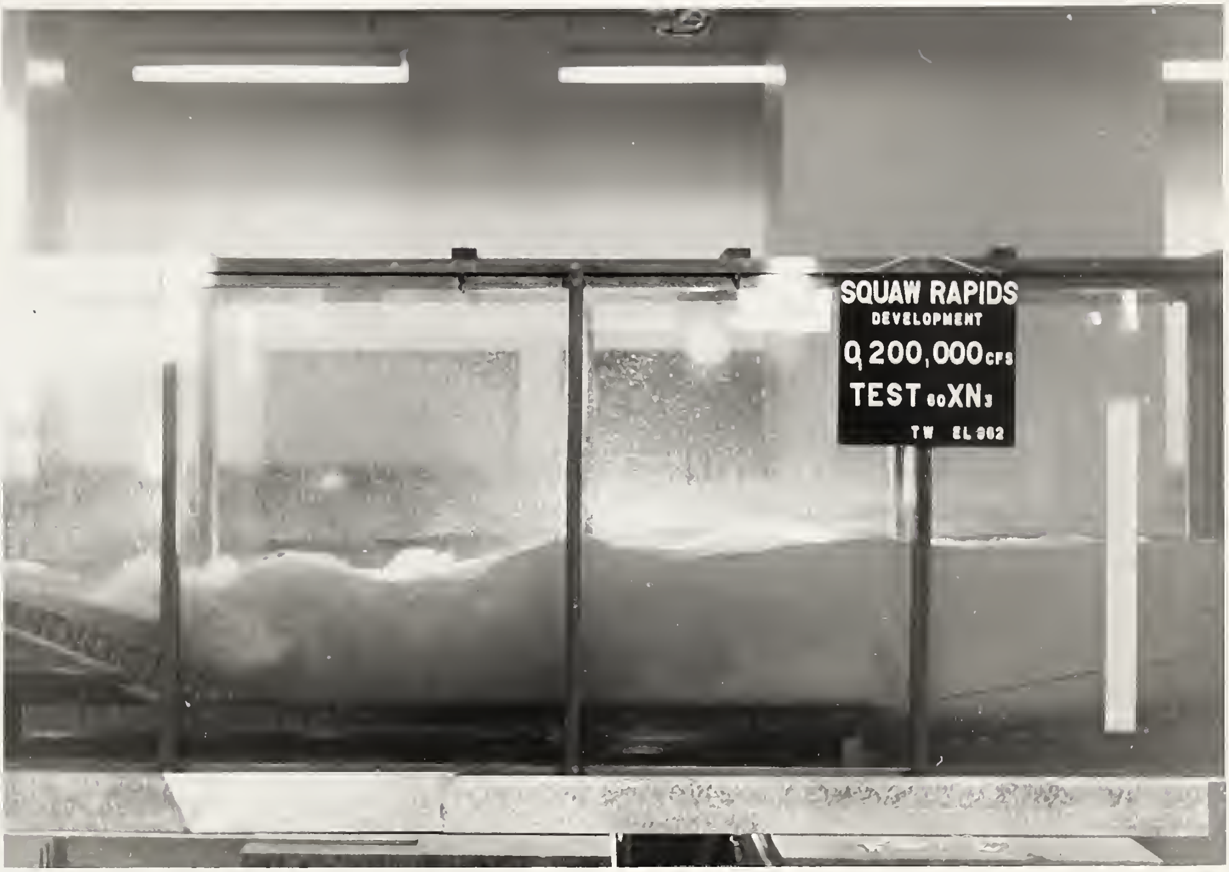
Hydraulic jump in the glass-walled flume.

Test No. 60XN2. (No chute blocks)



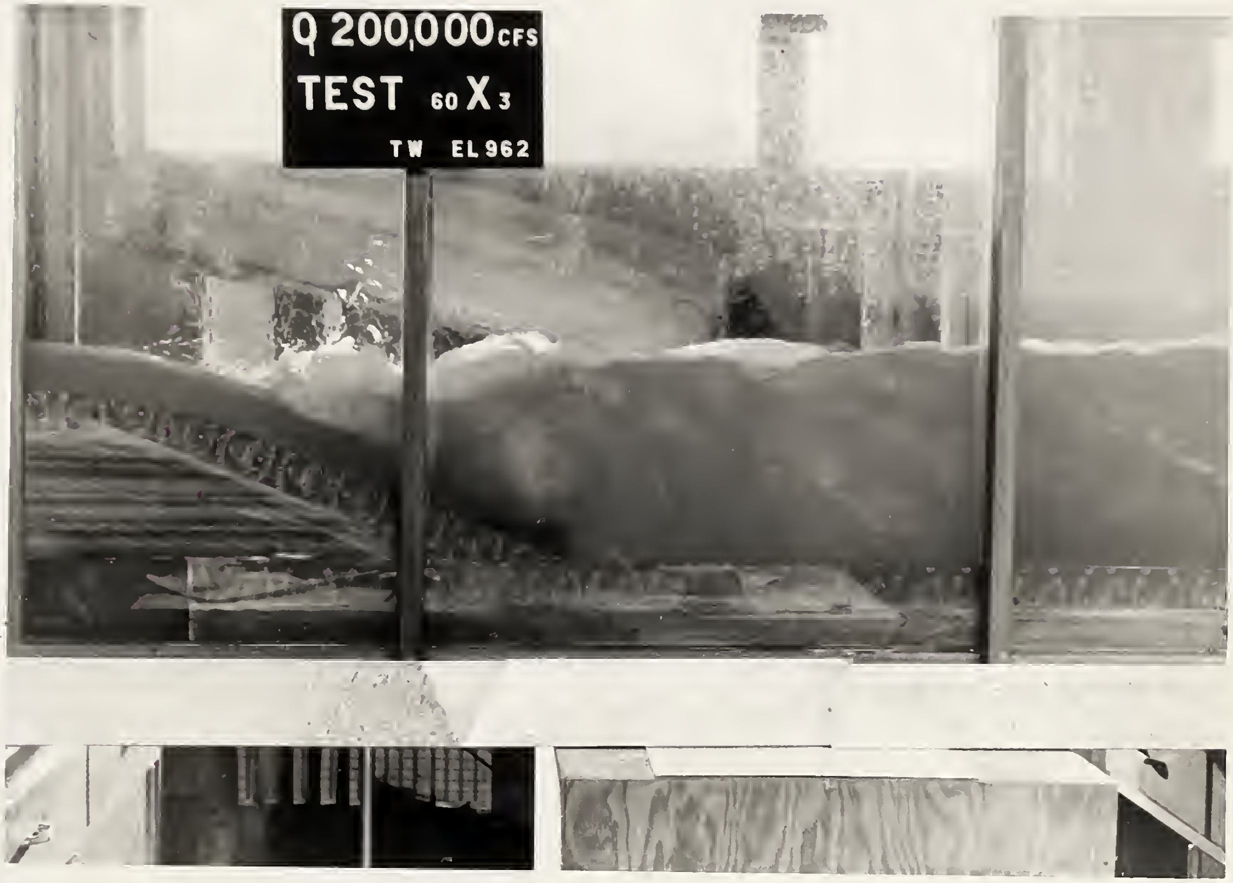
Hydraulic jump in the glass-walled flume.

Test No. 60X2. (Chute blocks in place)



Hydraulic jump in the glass-walled flume.

Test No. 60XN3. (No chute blocks)



Hydraulic jump in the glass-walled flume.

Test No. 60X3. (Chute blocks in place)

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